X-RAY REPAIR

A Comprehensive Guide to the Installation and Servicing of Radiographic Equipment

THIRD EDITION

JOSEPH J. PANICHELLO

X-RAY REPAIR

ABOUT THE AUTHOR

Joseph J. Panichello earned his B.S. degree in Biology from Pfeiffer University, an A.A.S. degree in Biomedical Equipment Technology from Stanly Technical College, and is AAMI certified. He has worked for over 30 years in x-ray servicing, both as an in-house BMET and as an x-ray field service engineer. He lives in Medford, New Jersey with his wife and daughter.

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By

JOSEPH J. PANICHELLO, CBET

CHARLES C THOMAS • PUBLISHER, LTD.
Springfield • Illinois • U.S.A.

Published and Distributed Throughout the World by

CHARLES C THOMAS • PUBLISHER, LTD.
2600 South First Street
Springfield, Illinois 62704

ISBN 978-0-398-09191-0 (paper)
ISBN 978-0-398-09192-7 (ebook)

First Edition, 1998
Second Edition, 2005
Third Edition, 2017

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Printed in the United States of America
MM-C-1

Library of Congress Cataloging-in-Publication Data

Names: Panichello, Joseph J., author.
Title: X-ray repair : a comprehensive guide to the installation and servicing of radiographic equipment / by Joseph J. Panichello.
Description: Third edition. | Springfield, Illinois : Charles C Thomas, Publisher, LTD., [2017] | Includes bibliographical references and index.
Identifiers: LCCN 2017025431 (print) | LCCN 2017027025 (ebook) | ISBN 9780398091927 (ebook) | ISBN 9780398091910 (paper)
Subjects: | MESH: Radiography--instrumentation | Equipment Safety
Classification: LCC RC78.5 (ebook) | LCC RC78.5 (print) | NLM WN 150 | DDC 681/.761--dc23
LC record available at https://lccn.loc.gov/2017025431

For Emily

PREFACE

It has been 20 years since the publication of the first edition of *X-ray Repair*. In that time, the field of Radiology has advanced in ways that would have been difficult to predict. The most notable change relates to the way images are recorded and stored. Film and film processing, which had been used in this field since the very beginning, are becoming a thing of the past. Since the second edition of *X-ray Repair* (2005), radiography has progressed from using x-ray film as the primary means of recording images, to using computed radiography (CR), and, finally, to digital radiography (DR). Within a few years of this writing, x-ray film and CR technology will no longer be used for medical imaging. Sadly, new students of radiographic technology will never know the art of x-ray filming. This third edition of *X-ray Repair* will focus on the transition to digital technology.

Fortunately for those who install and repair x-ray equipment–the x-ray service engineers–the basics of x-ray production still apply to the field of radiography. The x-ray generator, tube support, radiographic table, and wall stand are still needed to obtain an x-ray image. With digital imaging, most of the changes apply to image capture and post-processing.

Another change to healthcare, in general, relates to an aging population, which has changed the way we test, diagnose, and treat patients. Rather than traveling to the hospital, patients can travel shorter distances to smaller satellite medical facilities for their examinations. They can also go to urgent care centers located within their communities. This trend has led to a demand for compact, yet high-powered, x-ray units to perform the exams in these smaller facilities. But there are many older patients, or patients with disabilities, who cannot travel outside the home for their examinations. These "non-ambulatory" patients must be examined in their private residences, or at nursing homes and retirement facilities. In response, mobile x-ray has become a growing industry. Mobile x-ray machines are light and compact. When paired with a digital receptor, these units produce high-quality images for many of the exams commonly performed in hospitals and clinics. The images acquired in the home are transmitted instantly to secured servers where they can be accessed by radiologist for interpretation and diagnosis. This lighting speed technology is the way of the future. For this edition, I have expanded the chapter on mobile x-ray units to include the latest trends in mobile x-ray services.

A goal of *X-ray Repair* has always been to prepare the student who wishes to enter the x-ray servicing profession. This new edition has been completely rewritten and updated to focus on equipment currently in use, and to address the latest in digital imaging. With new illustrations and a revised chapter order, the book is more approachable to students. Discussions on film and film processing remain because it is important to understand the challenges that faced medical imaging in those early days, and to understand how digital technology developed. I have included calibration procedures as well as troubleshooting guidelines for digital equipment. With 33-plus years servicing x-ray equipment, I have witnessed many types of equipment failures. Included are some troubleshooting tips to help service engineers quickly narrow down the cause of an x-ray failure. Also, working directly in the mobile x-ray industry has allowed me to provide valuable insight into troubleshooting and repairing those "portable" units.

I hope this new edition will be of great help to students as well all the biomeds and service engineers currently working in the field. The goal of writing *X-ray Repair* has always been to shed light on this highly technical field.

JOE PANICHELLO

ACKNOWLEDGMENTS

I would like to thank Michael Payne Thomas and Charles C Thomas Publisher, LTD for publishing this book on x-ray servicing. It has been a pleasure working with Mr. Thomas over the past 20 years. I am grateful for the opportunity to write this third edition.

I would like to thank my wife, Caroline, for her patience and understanding while I was working on this edition–mostly on nights and weekends. This edition is dedicated to my daughter, Emily, who is graduating from college this year and will now embark on her own professional career.

THE LAWS OF X-RAY SERVICE

This book is intended to be used as a reference manual for field service engineers and in-house biomedical engineers when servicing radiographic equipment. It is also written to prepare the student of x-ray servicing for all the specific duties involved for the safe and proper maintenance of radiographic equipment. The goal is to provide standard servicing practices.

To be successful in this career, the engineer should always adhere to the "laws" listed below when servicing radiographic equipment.

THE LAWS

I. When radiographic equipment is installed properly, it will perform optimally and more reliably. When a failure does occur, it is more easily repaired.

II. If PMs are performed properly and at regular intervals, equipment failure rate will be reduced and the equipment will operate well beyond its predicted life expectancy.

III. When servicing equipment, if a problem is correctly diagnosed, properly repaired, and thoroughly tested after the repair, there will be no service recall.

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X-RAY REPAIR

Chapter I

THE DISCOVERY OF X-RAYS

The use of x-rays is so prevalent today that it is difficult to imagine how many industries, especially the medical profession, could function without their daily use. Indeed, most people have had some contact with x-rays in their lifetime and are aware of their importance. Doctors, structural engineers, research scientists, and airline security agents all use x-rays routinely in their respective careers. Hardly anyone would argue that the discovery of x-rays was one of the most important discoveries of our time. Mankind has certainly benefited from their use.

Because of their widespread use, it is difficult to imagine that x-rays were discovered a little over a century ago. And though there have been many advancements in radiographic equipment design since that time, most of the devices used today in general radiography very closely resemble those early units. The service engineer can gain a much better understanding of general x-ray theory by learning just how x-rays were first discovered and by following the development of the x-ray tube and radiographic system.

The discovery of x-rays, like many other important discoveries, occurred accidentally while scientists were experimenting with glass vacuum tubes. These vacuum tubes were made of thin-walled glass that contained two metal electrodes. They were partially evacuated by a mercury pump and then filled with a specific gas to create a visual effect. When a high-tension discharge from an induction coil was applied to the vacuum tube, beautifully-colored streams of light were produced between the two electrodes of the tube. These streams of light mostly were a source of fascination and curiosity for the scientists at that time. After further experimentation with improved vacuum tubes, scientists began to learn more about the streams of light. They determined that the stream of light originated at the negative "cathode" electrode within the tube and flowed to the positive "anode" electrode. In addition, as the tube's vacuum level was increased, the streams would likewise change in color and character, until they finally became invisible.

These "rays" were labeled cathode rays by William Crookes in 1878, who was the first to observe their directional properties while experimenting with vacuum tubes.[1]

During his experiments performed in the dark, Crookes noticed that the cathode rays appeared outside of the glass tube as a bluish glow. He later modified the glass tubes by placing an aluminum window in the tube so that the cathode rays could pass through more easily. These modified tubes then became known as Crookes Tubes and were commonly used for experimentation.

The cathode rays could easily pass through the aluminum window of the tube and would produce luminescent effects on phosphor materials. They would also affect photographic plates. These rays, however, were of very low energy and, consequently, would be absorbed in only a few centimeters of air. Unfortunately, Crookes had not realized that what he was actually observing were low energy x-rays.

Seventeen years later, scientists were still experimenting with the Crookes Tubes. Philip Lenard demonstrated that the cathode rays scattered in all directions at the point where they exited the aluminum window. He also made shadow pictures, termed "sciagraphs" on photographic plates. After performing many experiments, he concluded that there was another unidentified component to the cathode rays.

The person credited with the discovery of "x-rays" was a German physicist by the name of Wilhelm Conrad Roentgen. Roentgen was born in Lennep, Germany, in 1845. By the age of 24, he had already published many scientific papers on the properties of gasses. During his career as professor and scientist, he published more than 40 papers on scientific phenomena and was highly respected by his fellow scientists.

It wasn't until June of 1894, at age 49, however, that Roentgen began to experiment with vacuum tubes. Roentgen began his own experiments with the Crookes Tubes and made several important observa-

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1. The cathode ray phenomenon was commonly used in early video monitors which used a CRT (cathode ray tube).

tions. He noticed that he obtained better results when the tubes were highly evacuated, and he would often spend days evacuating a tube for his experiments. Also, he felt that if more current was applied to the tubes, cathode ray production would increase. Incidentally, he damaged many tubes during his experiments and thus began using heavier walled tubes.

While experimenting with the modified tubes in the fall of 1894, he noticed a faint glow appearing in the room that precisely coincided with the discharge of the Crookes Tube. To be certain that the light was not coming from the tube or from the induction coil, he completely covered the Crookes Tube with cardboard so that no light could escape. He also covered the induction coil completely to eliminate any light caused by arcing within the machine. To his amazement, the glow still appeared in the darkened room.

The source of the glow turned out to be a screen made of a photographic material (barium platinocyanide) that was located several feet away from the tube. Some heretofore unknown invisible energy was being emitted from the vacuum tube and was traveling across the room, exciting the photographic screen. This was a highly significant observation since cathode rays had never been known to travel more than a few inches from the tube.

Roentgen experimented with the "new kind of ray" for nearly a year before he published his findings. On November 8 of 1895, at age 50, he presented his paper "The First Communication," announcing his discovery.[2]

He called the mysterious rays "x-rays," using the letter "x" (the mathematics symbol) to represent the "unknown" energy. Along with his paper he included several fascinating photographs that he had obtained by using the x-rays. These x-ray photographs included a metal compass, a box containing scientific weights, a double-barreled shotgun, and various types of metals.

Of all the published photographs, however, the one that immediately caught the attention of the media and of the public was the x-ray photograph of the hand of Bertha Roentgen, his wife. This famous photograph, showing all the bones in her hand including the two rings on her finger, was to change the course of medicine forever.

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2. Coincidentally, I was writing the first edition of this book on November 8, 1995, marking the 100-year anniversary of this great discovery.

In fact, Roentgen's x-rays proved to be the fastest spreading discovery of all time. Within months of the discovery, x-rays were commonly being used by physicians to diagnose bone fractures and to locate bullets in wounds from gunshots. X-rays were used so successfully that many overenthusiastic scientists predicted that the use of x-rays would eliminate the need for vivisection completely. In May of 1896, the first journals completely dedicated to x-ray photographs appeared in the United States. By January of 1897, many hospitals had x-ray departments.

In Germany, the first x-ray machines were being manufactured as early as February of 1896. These early machines required long exposure times–4 to 20 minutes, depending on the area being radiated–and, consequently, needed to be improved. It was then discovered that if a fluorescent screen was placed on both sides of the radiographic film, the exposure time would be reduced significantly. This finding led to the widespread use of intensifying screens in film cassettes.

Because of the great demand for x-ray equipment, manufacturing companies all over the world began to produce x-ray machines. Roentgen never applied for a patent on his x-ray apparatus because he felt his discovery was for the public benefit and not for his own profit. As a result, a complete x-ray system could be purchased for less than $150. A portable x-ray machine, complete with a coil, condenser, two sets of tubes, a battery, and a handsome carrying case could be purchased for the price of about $15. X-ray tubes could be purchased for less than $4 a piece.

The public's fascination with x-rays and their effects was immense. Everyone wanted to see, for themselves, the effects that x-rays produced and wanted to view their own bones. At the Electrical Exhibit in New York in May of 1896, Thomas Edison showed the world the first fluoroscope. With the fluoroscope, the internal structures of the body could be viewed directly on a fluorescent screen in real time, eliminating the usual wait involved for photographic plates to be developed. A person would simply place their hand directly in the x-ray beam and watch the bones of their fingers moving around, which was very exciting (and fun) to see. The immense popularity of the fluoroscope contributed to the widespread public use of x-rays.

Roentgen disapproved of this superficial use of his invention because he knew the effects of x-ray radiation had not yet been fully investigated. In fact, whenever he worked with x-rays, he would shield himself with a lead barrier from direct exposure to the rays as a precaution. Sure enough, soon after his discovery, news began to surface of injuries that were related to x-ray radiation. Among the reported injuries were burns, hair loss, and the swelling of radiated tissue. Most injuries occurred to doctors and demonstrators of the x-ray equipment.

Clarence Madison Dally, a glassblower and Edison's longtime assistant, regularly demonstrated the fluoroscope to the public. He later died from burns contracted from the continuous exposure to x-rays, becoming the first fatality resulting from radiation exposure. As of October, 1959, 359 deaths were attributed to excessive radiation exposure.

The early scientists who investigated x-rays were aware that tissue was affected, or changed, by radiation and warned the public of the potential hazards to tissue. This secondary characteristic of radiation, that it could destroy tissue, eventually led scientists to explore the field of Radiation Therapy.

X-ray machines were commonly used during wartime, significantly reducing the number of deaths due to battle injuries. In addition, many improvements in x-ray techniques were made because of the findings of the military. Surgeons noticed that the closer the x-ray tube was to the patient, the more the patient was likely to suffer radiation burns. Because of this finding, a minimum distance of 10 inches of separation (between the x-ray tube and the patient) was established. Also, a maximum exposure time of 30 minutes was established for all patients.

Many significant changes in x-ray tube design were subsequently made. Roentgen designed the first focused x-ray tube in February of 1896. Thomas Edison found that better penetrating x-rays could be produced when cooling the x-ray tube by immersing it in oil. Also, higher voltages could be used while the tubes where immersed in oil. Many of the inventions of scientist Nikola Tesla, including his high voltage induction coils, helped to produce better quality x-rays.

By the early 1900s, x-ray tubes began to resemble present day tubes. In 1913, W. D. Coolidge of General Electric Company developed the hot cathode tube (thermionic tube) to allow for control of the amount of tube current (or mA). Coolidge also used tungsten in the construction of the target to provide greater tube stability. Ludwig

Zehnder, who was Roentgen's assistant for many years, invented a metal-shielded x-ray tube to protect doctors and technicians from stray radiation. The Phillips Company of the Netherlands eventually improved on this design and developed the "Metalix-Tube" which used a metal housing to surround the glass vacuum tube.

On December 10, 1901, Wilhelm Conrad Roentgen received the Nobel Prize in Physics for his work with x-ray radiation. He spent the rest of his life exploring physical properties of matter and continued scientific experimentation with crystals even after his retirement in October of 1919, at age 75. He died on February 10, 1923.

The period from around 1910 to 1950 was considered the "golden age of radiology." During this time, x-ray tubes and all other x-ray devices advanced in design to their present-day status. Major advancements included: (1) the hot cathode tube (1913) for controlling tube current; (2) the first shockproof portable x-ray unit (1919), which employed the first shockproof high voltage cables; (3) the vibrating Bucky (1923), which greatly reduced scatter radiation; (4) the high voltage rectifying switch (1910), which applied both alternations of the AC line to the x-ray tube, effectively doubling the radiation output; (5) oil immersed, rotating anode tube (1939), which greatly increased the output of the x-ray tube; (6) the tilting table (1943), which allowed radiologists to obtain the different anatomical views required for proper diagnosis; and (7) intensifying screens (1912), which reduced the required exposure time significantly with the results of longer x-ray tube life and reduced patient dose. Many of the items listed above can still be found in today's radiographic rooms without significant change to the original design.

The general radiographic room has been around for over 100 years and will continue to be the dominant mode for diagnostic imaging well into the future. Although advances in other medical imaging modalities (i.e., CT or MRI) have provided physicians with alternative methods to view the internal structures of the human body, general radiography studies remain the primary diagnostic tool.

Chapter II

THE FUNDAMENTALS OF X-RAY PRODUCTION

In writing this book, the author assumes that the reader has a basic knowledge of x-ray theory. The objective here is to give a brief overview of x-ray production to ensure that there is a common starting point before discussing the servicing of x-ray equipment. If a more detailed discussion of x-ray theory is required, there are many resources available in books and online that deal specifically with the subject.

In a vacuum tube, if electrons are accelerated by a force and made to collide with a stationary object, energy will be released. The energy released is a result of the sudden deceleration of the electrons caused by the impact with the object. If the force applied to the tube is great enough to accelerate the electrons to a sufficiently high speed, and the object is made of the proper material, the energy released from the collision will be in the form of heat energy, but with a very small amount of high frequency electromagnetic radiation. The frequency of this radiation is much higher than visible light (10^{18} hertz) and is called x-ray radiation (Figure 1).

Here we have one of the most important concepts of x-ray production; a fact that should be permanently ingrained in the service engineer's memory. Specifically, during x-ray production, 99 percent of the energy released is given off as heat and 1 percent is in the form of useful radiation. This fact helps explain why x-ray tubes fail and will be discussed in detail later in the troubleshooting section of this book.

X-rays are produced in a thermionic vacuum tube called an x-ray tube. Thermionic x-ray tubes consist of a negative electrode (or cathode), and a positive electrode (or anode), enclosed in a glass envelope

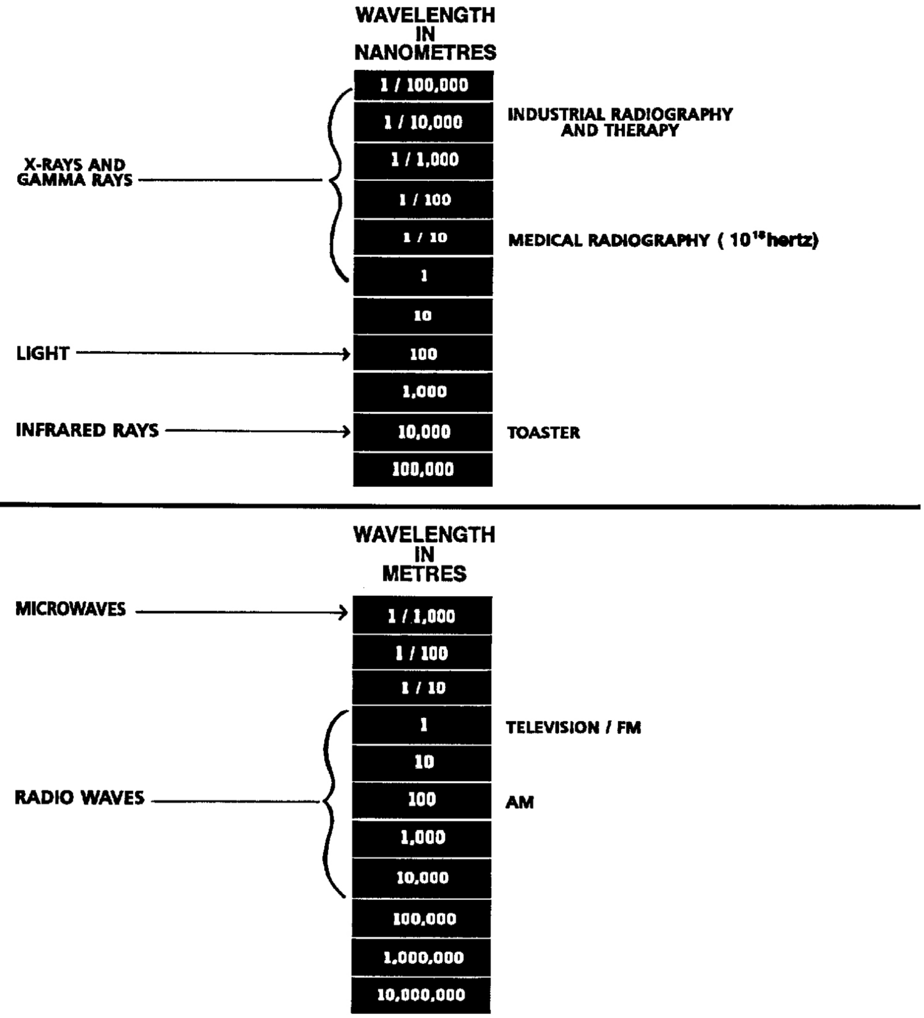

Figure 1. The electromagnetic spectrum.

(Figure 2). The glass envelope is surrounded by insulating oil and completely encased in a lead lined metal housing which contains a port or window through which the x-ray radiation exits.

As shown in Figure 2, the cathode consists of a thin wire called a filament. This filament is like the filament found in an incandescent light bulb but is surrounded by a focusing cup which concentrates, or focuses, the electron beam. The filament, when heated, will liberate free electrons that will eventually collide with the anode. Liberating electrons by using heat in the manner described above is referred to

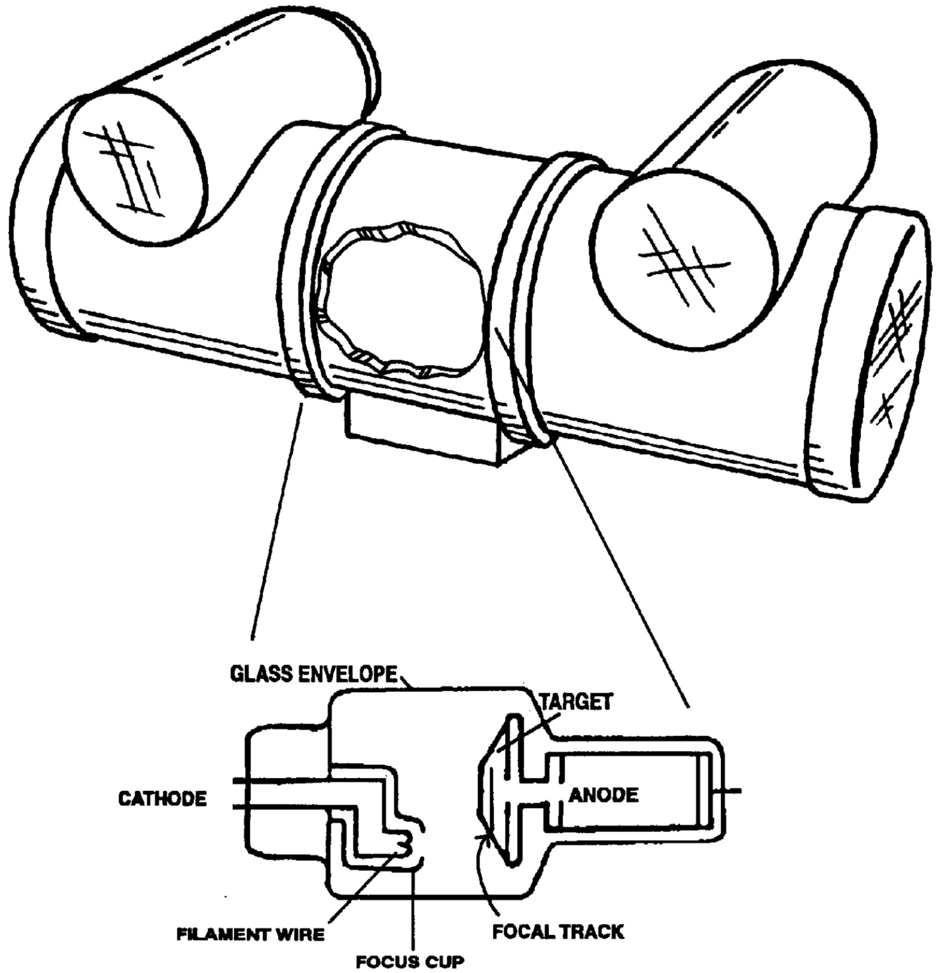

Figure 2. The x-ray tube. The x-ray tube glass envelope is surrounded by insulating oil within the tube housing.

as thermionic emission. The amount of filament heating dictates the number of electrons that will be liberated, and consequently, the amount of x-ray tube current (or mA). Controlling the heating of the filament is referred to as filament control.

The anode or positive electrode contains the target, which is made of a special material (e.g., tungsten) that has a high melting point and a high atomic number. High atomic numbers are used to ensure that the x-ray beam will contain photons of a high-energy level. When the electrons collide with the target, x-rays are emitted in all directions from the target. To ensure that radiation will only exit through the port of the tube, the metal housing of the x-ray tube is completely lined with lead.

The force that causes the electrons to travel at a high rate of speed is a high voltage potential that is applied across the anode and cathode of the x-ray tube. The amount of high voltage not only affects the quantity of radiation but also affects the quality or penetrating ability of the x-rays (see Chapter V). Regulating the high voltage is called kVp control.

In short, to produce x-rays in a thermionic tube, there must be: (1) a filament voltage supply applied to the filament wires of the tube; and (2) a high voltage potential applied across the x-ray tube. If either of these supplies is missing, x-rays cannot be produced.

Chapter III

THE X-RAY SYSTEM

A typical x-ray system consists of an x-ray control, a high voltage transformer unit, and an x-ray tube (Figure 3). The x-ray tube and high voltage transformer unit found in most general radiographic rooms are connected by special high voltage cables. In some designs, especially in mobile x-ray units, the high voltage transformer unit and x-ray control are combined as one unit and together are referred to as the x-ray generator (see Figure 43). In this case there are no high voltage cables required.

THE X-RAY CONTROL

Three factors control the quality and quantity of x-rays produced. They are: kVp (or kV), mA, and time. These three factors are regulated in the X-ray Control. KVp refers to the amount of high voltage, or peak kilovoltage, applied to the x-ray tube. MA is the amount of current, or milliamps, that is passing through the tube. Time refers to the exposure time, which is the period that the x-ray tube is energized and emitting x-ray radiation. Each of these three factors has an important effect on image quality, which will be discussed in detail later in this book (Chapter V). For now, our discussion will concentrate on the most common types of x-ray generators.

There are four basic types of generators: single-phase, three-phase, constant potential, and high frequency. Each generator type creates and regulates the kVp by different means. Consequently, each generator type produces a distinct kVp waveform which can be viewed on an oscilloscope.

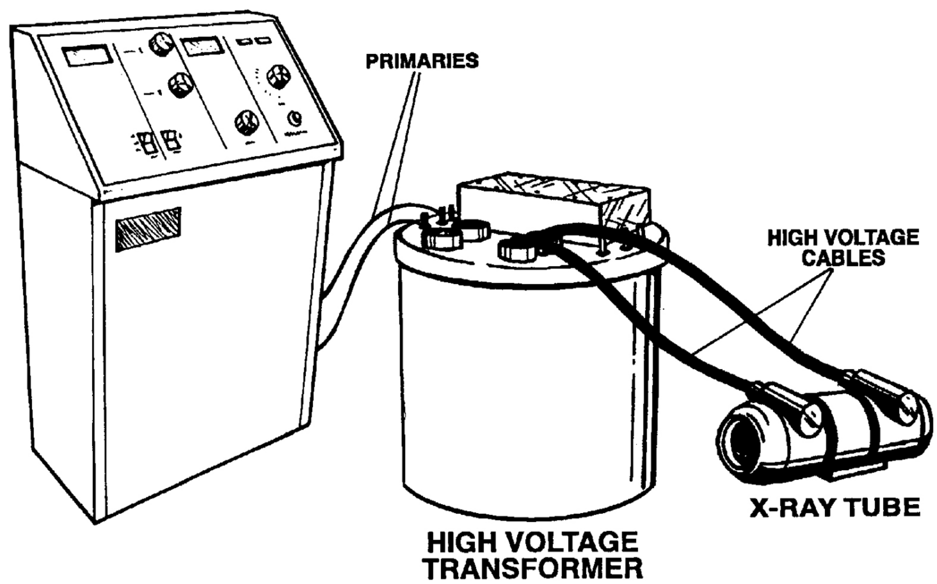

Figure 3. A typical x-ray system.

kVp Control

The Single-Phase Generator

The single-phase generator was the first type of x-ray generator manufactured and is the most basic in design. Although they are still commonly used today, they remain the least efficient generator in producing radiation and expose the patient to significantly more radiation per exposure than the other types of generators. However, because they require only a single-phase power line, are physically smaller in size, and are the most affordable of all generators, many customers, especially in smaller outpatient facilities, consider this type of generator the generator of choice. Furthermore, because of the simple design with fewer components, single phase generators are easy to service. However, with the many advantages offered by high frequency generators, the single-phase generator will soon be replaced by the more efficient high frequency generators discussed later in this chapter. Still, it is important to understand the theory of how single-phase units operate.

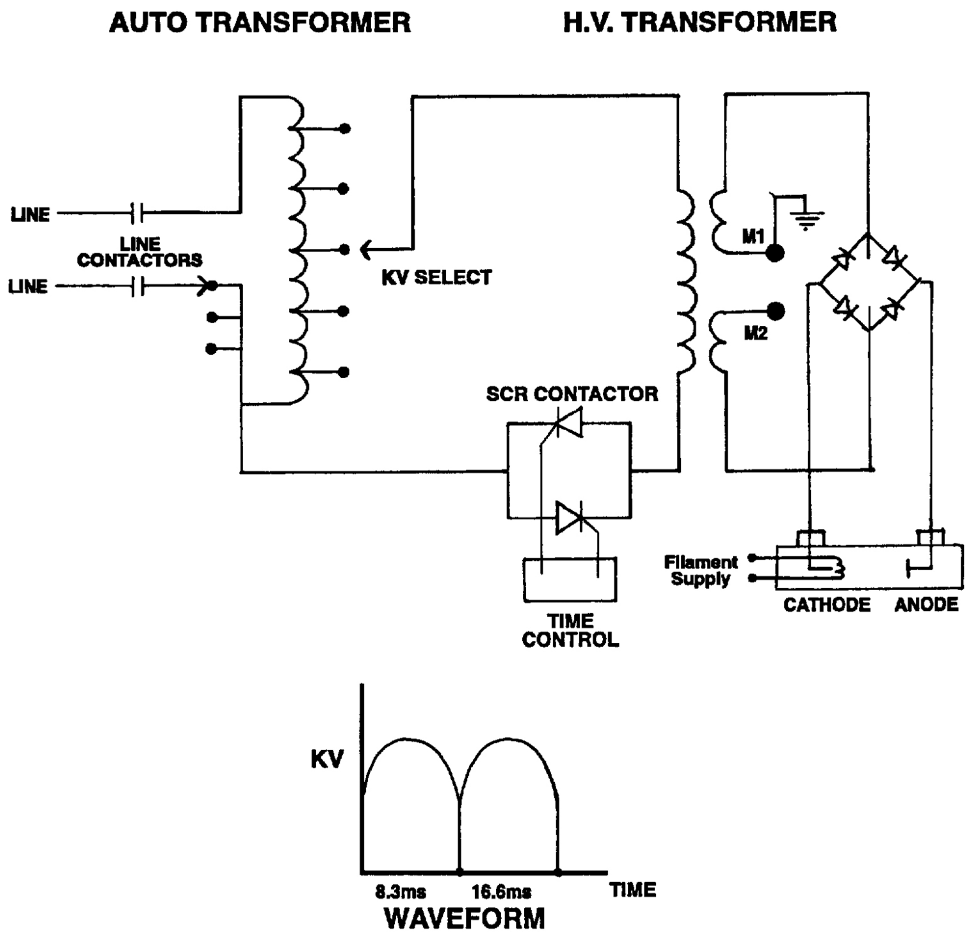

Figure 4. Single-phase generator and output waveform. Single-phase generators produce an output waveform with 100 percent ripple.

In this design, a primary voltage corresponding to the selected kVp is outputted from the autotransformer and applied to the primary coil winding of the high voltage transformer (Figure 4). The primary voltage is then stepped up (or increased) through the secondary of the transformer to the desired high voltage, which is rectified (i.e., converted to DC), and then applied to the x-ray tube.

From the diagram we see that a single-phase generator is easily identified by its characteristic, 100 percent ripple, DC waveform. Since useful radiation is produced only during the peak portion of the waveform (approximately 30% of each pulse), this type of generator is not very efficient at x-ray production.

The Three-Phase Generator

Three-phase generators are a great improvement over single-phase generators in that they can deliver more power, are more efficient at producing x-ray radiation, and provide more accurate time control. Three-phase generators require three different line phases for input power, each phase being 120° out of phase with the other two. Instead of a single autotransformer, these generators have three separate, usually motor driven, autotransformers–one for each phase. The voltage that is derived from the autotransformers is applied to the primary of a special three-phase, high voltage transformer.

There are two types of three-phase, high voltage transformers used in these x-ray generators. The type of transformer, and its corresponding output waveform, depends on the type of secondary winding configuration employed (Figure 5). In the first type of transformer, the secondary could be configured with two separate Delta winding, or two separate Wye (or Star) windings. The second type combines both types of windings in the secondary in a "Delta-Wye" configuration. If the same winding configuration is used in the secondary, it is termed a six-pulse generator. A Delta-Wye winding configuration designates a twelve-pulse generator.

A six-pulse generator produces a DC output waveform that has 13.5 percent ripple. This is a significant improvement over single-phase generators. A twelve-pulse generator, however, produces an output waveform with only 3.4 percent ripple. By examining the kVp waveforms, it becomes evident that a twelve-pulse system is more desirable because of its near "constant potential" DC waveform.

Three-phase generators provide many advantages over single-phase units. The increased output efficiency of these generators allows for much shorter exposure times, as compared to a single-phase generator using the same kVp setting. In addition, because of the larger input line voltages used (i.e., 480 VAC), much higher exposure techniques can be used with three-phase systems. Also, the exposure time is more accurately controlled in three-phase generators, a requirement for serial radiography and phototiming techniques. For these reasons, three-phase generators are frequently used for angiographic and spot filming applications.

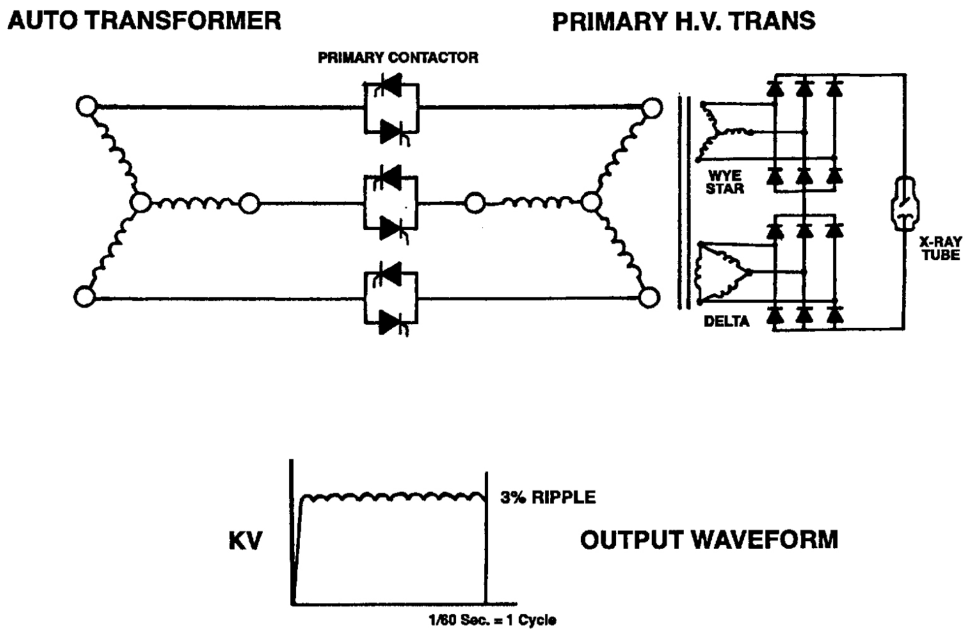

Figure 5. Three-phase generator (12 pulse) and output waveform. These generators produce an output waveform with only 3.4 percent ripple.

The Constant Potential Generator

A special version of a three-phase generator is called a constant potential generator. Here, additional switching circuitry is employed in the high voltage secondary circuit to achieve the accurate exposure time control required for high-speed filming applications. Because this type of generator utilizes a high voltage switch, the exposure times are more precisely controlled and, in addition, the resulting kVp waveform is a ripple free DC square wave (Figure 6). With a true square wave output, the kVp remains constant for the duration of the exposure, hence the name "Constant Potential." Constant potential generators were generally the most expensive generators available and were most often used in Cath Lab and Special Procedure applications.

One way the fast switching of the high voltage is accomplished is by using tetrodes in the high voltage secondary. The tetrodes, located in a separate "tetrode tank," are wired in series with the x-ray tube. An external exposure signal, sent from an imaging device such as a cine

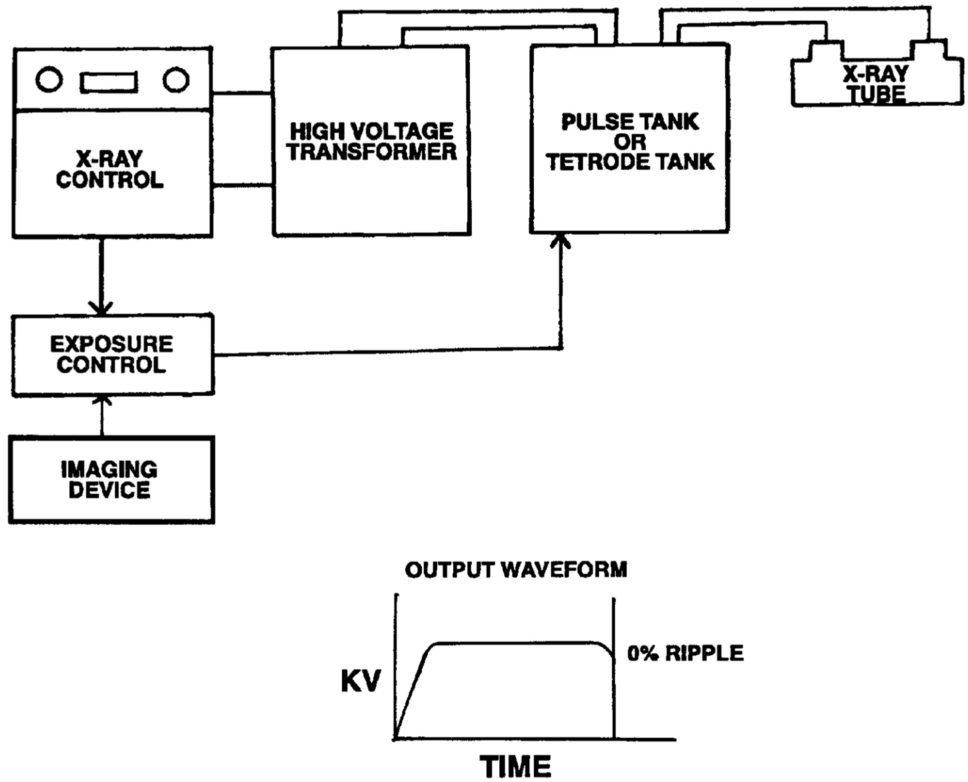

Figure 6. Constant potential generator block diagram and output waveform. Constant potential generators produce an output without ripple.

camera, or from a handswitch in radiographic mode, turns the tetrodes on and off which, in turn, allows the x-ray tube to conduct.

Another way to accomplish fast switching is by using a grid-controlled x-ray tube. With a standard x-ray tube, the grid (focusing cup) of the tube is normally shorted to the common reference point. With a grid-controlled x-ray tube, the grid is held at a negative potential (in relation to the cathode) and is essentially switched "off" even when high voltage is applied to the x-ray tube. During an exposure, the grid voltage is pulsed on and off and, in turn, the x-ray tube is turned on and off by pulses sent from a pulse tank. As with the tetrodes, the pulse tank receives an exposure signal from an imaging device to initiate an exposure.

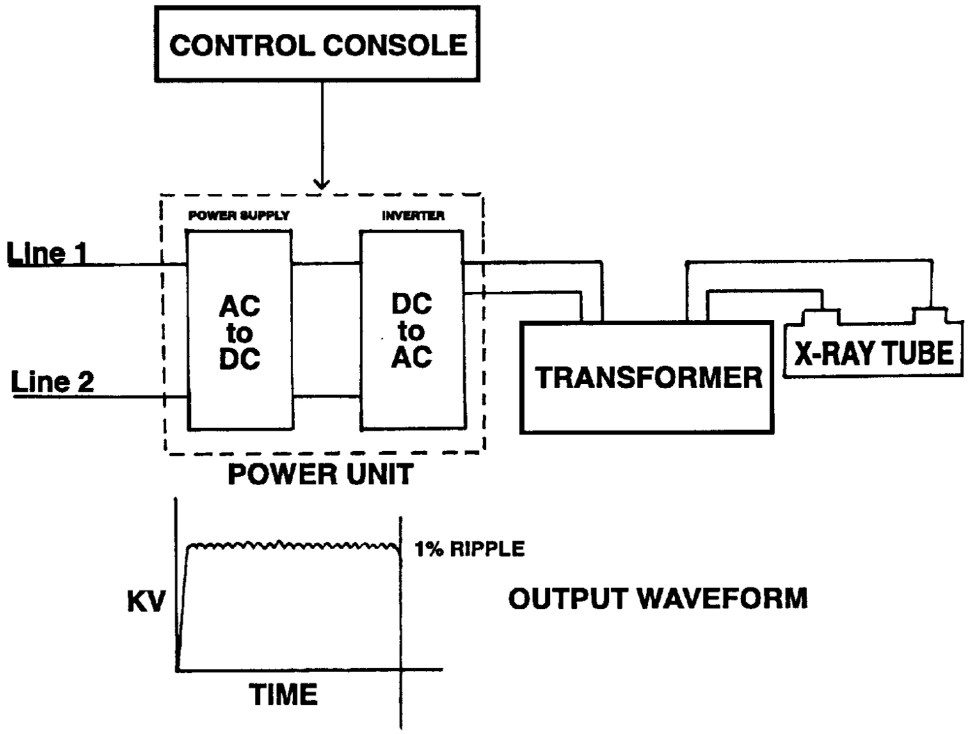

Figure 7. High frequency generator block diagram and output waveform. High frequency generators produce an output waveform with less than 1 percent ripple.

The High-Frenquency Generator

High-frequency generators are the latest design and are, by far, the most efficient at producing x-ray radiation. This type of generator can produce a high voltage square wave that is essentially ripple free, providing uniform radiation for the entire exposure duration. Another advantage of the high-frequency generator is that it can operate with either a single-phase or a three-phase input line and with a wide range of input voltages. Because it operates at high frequencies, the electronic components can be reduced overall so that the generator footprint is more compact.

By looking at the simplified block diagram (Figure 7), it is shown that high-frequency generators utilize a unique method for producing high voltage. The incoming AC line voltage is fed directly into a DC power supply (400 VDC, for example), which is used to supply the power inverter. The power inverter, which is a device commonly used in electronic applications, converts the DC voltage to high frequency square wave pulses that are used to drive the high voltage transformer. The frequency of the pulses is dictated by equipment design and can range from as little as 100Hz to as much as 400kHz or greater. The pulses are regulated to obtain the correct kV which is applied to the x-ray tube.

High-frequency generators represent a major advancement in generator design in that they provide much improved kVp regulation. With all other generator designs, the high voltage is derived directly from the AC line. Consequently, any fluctuations in the incoming power line will cause a corresponding fluctuation in the kVp waveform. With high-frequency generators, the constant DC supply maintains a stable output regardless of any inconsistencies with the AC line. Another advantage of using a high-frequency supply is that significantly smaller components can be used in the generator circuitry.[3]

This means that the high voltage transformer, which usually takes up a large area, can be placed inside the control cabinet along with the other components of the generator control. This greatly reduces the amount of space needed for an x-ray room installation. In many cases, the size limitation of the room is a major consideration in the purchase of radiographic equipment. In such situations, then, high-frequency generators are the ideal choice. Also, by using smaller components these generators are less costly to produce.

Other advantages of high-frequency generators are that they are much easier to calibrate, they will hold a stable calibration for a longer period of time, and provide more accurate time control as compared to the other generators. These advantages result from the fact that all high frequency generators utilize feedback loop circuitry to monitor (in real time) the actual kVp, mA, and time of the exposure. In addition, because of the fault monitoring capabilities of high-frequency generators, they are easier to troubleshoot and repair. Most high-frequency generators have error detection circuitry that can isolate specific failures and even provide a message on the console display to alert the operator of a problem. With the many advantages offered by

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3. Basic electronic theory demonstrates why this is so. Referring to the formulas for capacitive and inductive reactance $X_L = 1/2 \neq FC$ and $X_L = 2\neq FL$, it can be seen that if all other factors are held constant, increasing the frequency would require a corresponding decrease in capacitance and inductance respectively and, therefore, smaller components.

high-frequency generators, they have become the generator of choice for many medical imaging applications.

MA Control

In addition to controlling the kilovoltage, the x-ray generator also controls the amount of tube current flowing through the x-ray tube. With x-ray tubes, the amount of current is measured in the lower milliamp range and is referred to as mA, for short. The way to control mA is to vary the amount of current going through the filaments of the x-ray tube. For a given increase in filament current there is a proportional increase in mA (kV held constant).

The current that flows through an x-ray tube is difficult to regulate. The reason for this is because the x-ray tube acts as a varying load depending on how much current is passing through it. This fluctuating load requires a highly efficient filament power supply to maintain constant current during the exposure. A typical design for mA control used in many x-ray generators consists of (1) a filament voltage regulator (originally called stabilizers) that provides a constant supply voltage to the filament circuits as the load varies and (2) the means of controlling the voltage that is applied to the filament transformer (Figure 8). Filament voltage regulation is accomplished in different ways, including resistor tap selection and frequency control.

The difficulty with mA control involves a phenomenon in x-ray tubes called space charge effect. Space charge is defined as the cloud of electrons that surrounds the filament when it is being heated. The size of the cloud is proportional to the degree of filament heating. The problem when dealing with the space charge phenomena is when we consider the kVp that is applied to the tube. If the filament current is held constant, an increase in kVp will cause a proportional increase in tube current because of the greater "pull" exerted on the electrons in the cloud. Conversely, a decrease in kVp will cause less pull on the cloud of electrons and this will reduce the actual tube current. Space charge compensation is employed specifically to maintain a constant mA through the full range of kVp settings.

With basic generator designs, the space charge compensation circuit is connected to the filament circuit at a point after the mA adjusting resistors. This circuit monitors the selected kVp and then applies the appropriate compensating voltage that is needed to maintain the

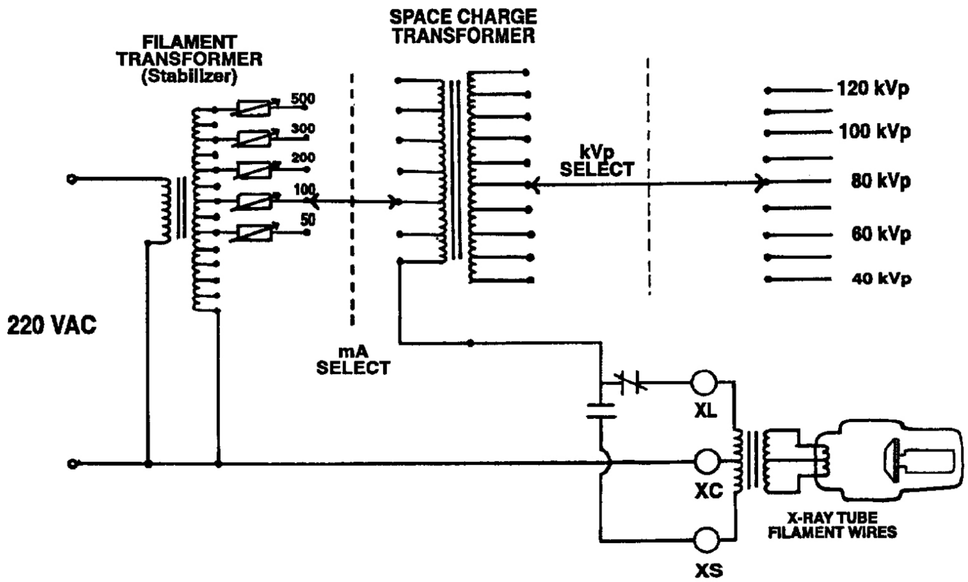

Figure 8. Filament control circuit. A correction voltage is applied to the filament wires to compensate for the space charge effect. The correction voltage is determined by the kVp selected.

selected mA at a constant level. At higher kVp settings, the space charge compensation circuit will reduce the voltage that is applied to the filament transformer, and at lower settings the compensation voltage will be increased. Generally, there is no space charge compensation applied at or near 80 kVp. Because of this fact, the preliminary mA calibration is performed at this kVp station (see x-ray calibration in Chapter VII).

Space charge compensation circuits are required for most x-ray generators. Since high frequency generators employ feedback loops and digital control to accurately control mA there is no need for additional circuitry for space charge compensation. The reader should, however, understand how space charge can affect tube current and note how x-ray generator designs, historically, have dealt with this phenomenon.

The Falling Load Generator

A primary cause of x-ray tube failure is related to filament damage caused by excessive tube currents. The constant use of higher mA's

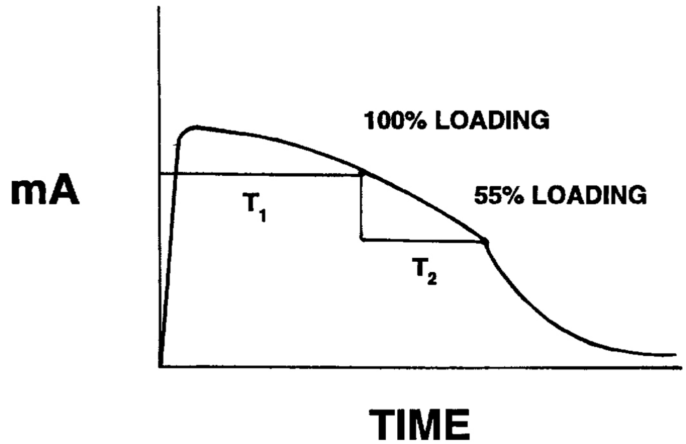

Figure 9. Falling load generator mA waveform. After a programmed time interval (T_1), the mA is reduced to a lower value for the remainder of the exposure. This design effectively extends x-ray tube life.

will shorten the life of an x-ray tube (see Chapter IX). To address this problem, some manufacturers of x-ray equipment developed a special type of generator for the specific purpose of increasing tube life. This type of generator is called a falling load generator and is named after the actual mA waveform that it produces.

Whereas, all other x-ray generators are distinguished by their kVp waveform, falling load generators are identified by the mA waveform. With falling load generators, the exposure begins with the highest mA allowable (for that x-ray tube) at a given technique setting. After a set time (e.g., 10 ms) the mA is significantly reduced producing the distinctive falling load mA waveform (Figure 9). The mA waveform continually "falls off" or decreases during the entire exposure, thus applying much less stress to the x-ray tube filaments.

This falling load design will increase x-ray tube life, but at a cost: longer exposure times that are required to compensate for the reduced tube current (after T_1). The long exposure times can cause a reduction in image quality mainly due to patient motion (see Chapter V). This major disadvantage partly contributed to the decline in use of the falling load generator. Moreover, because of advances in x-ray tube design and the increased popularity of high frequency generators, falling load generators are no longer in demand.

Time Control

Time Control is the third major function of the x-ray generator control and is accomplished in different ways depending on the type of generator. The timer circuitry must initiate the x-ray exposure and then accurately stop it at the selected time. In effect, the timer acts by alternately switching the primary voltage of the high voltage transformer on and off thereby turning radiation on and off.

In the early designs of x-ray units, the actual switching was done by large relays called contactors. Those service engineers at that time would look for the familiar loud clapping sound as the large contactor closed, signaling the exposure command as part of their normal troubleshooting process. Today, SCR's (silicon-controlled rectifiers) and other solid state devices such as IGBT's (Inverted Gate Bipolar Transistors) are used switch on the primary voltage to the high voltage transformer, instead. Solid state devices are used because they provide transient-free switching and are easily controlled by digital time control circuits.

Single-phase units, historically, had used analog timers, but today most use digital timing. With single-phase timing circuits, the AC waveform of the primary circuit is monitored for the zero cross-over points. The zero cross-over points are converted into timing pulses and are used to initiate, measure, and stop the exposure.

The diagram in Figure 4 demonstrates that each alternation of the AC sine wave (or 1/2 cycle) is 8.33 milliseconds in duration, and, therefore, the shortest possible exposure obtainable with a single-phase generator is precisely 8.3 milliseconds (1/120 s). This limitation presents a problem when high-speed imaging techniques are required, which may use 5 milliseconds or less. Even for conventional radiography, exposure accuracy is reduced when using short exposure times with single-phase generators.

Three-phase generators can use either analog or digital timers depending on the vintage of machine. However, the important issue with respect to three-phase timers is the method used to terminate the exposure. Two methods are commonly used, self-commutation and forced commutation, and it is important to understand the difference between the two.

X-ray generators that employ self-commutation utilize a contactor (two SCR's) for each line phase. With self-commutation, the exposure will terminate at the next zero cross-over point following the exposure stop signal (Figure 10). The diagram shows that two line phases must turn on to make a return path for the primary circuit. Thus, it takes 2.7 milliseconds for the anode plus 2.7 milliseconds for the cathode to turn on. This means that the shortest possible exposure time is 5.44 milliseconds.

Although an improvement over single-phase units, the response time is still not quick enough for high-speed modalities such as CT and catheterization labs. One solution for older units that employ self-commutation timing control was to add on additional external circuits that could force the SCR's off when an x-ray stop command is generated, allowing for exposure times as short as one millisecond. These units are referred to as forced extinction packages.

The second type of three-phase timer utilizes forced commutation to terminate the exposure. The forced commutation design solves the problem of exposure termination by utilizing two SCR contactors and a bridge network at the midpoint of the primary winding of the high voltage transformer (Figure 10).

One SCR contactor completes the path of the primary circuit which then initiates the exposure. The second SCR contactor forces the SCR that initiated the exposure to "off" by reversing the anode-cathode polarity. Exposure times as short as 1 millisecond are possible with forced commutation.

Core Memory Circuits

Another important function of the time control circuits is to provide core memory detection. The iron core of high voltage transformers, or any solid core transformer for that matter, must see alternate cycles of polarity to function properly. If, for example, the positive cycle of the AC waveform was the last cycle to pass through the primary of the transformer, the next exposure must begin with a negative alternation. If the same polarity were to follow, the iron core would become "saturated," a condition that severely affects the performance of the transformer. Core saturation will result in reduced efficiency of the transforms and will usually cause a serious high voltage failure (see Chapter IX).

Core memory circuits prevent the iron core from becoming saturated by monitoring the polarity of the primary signal and, conse-

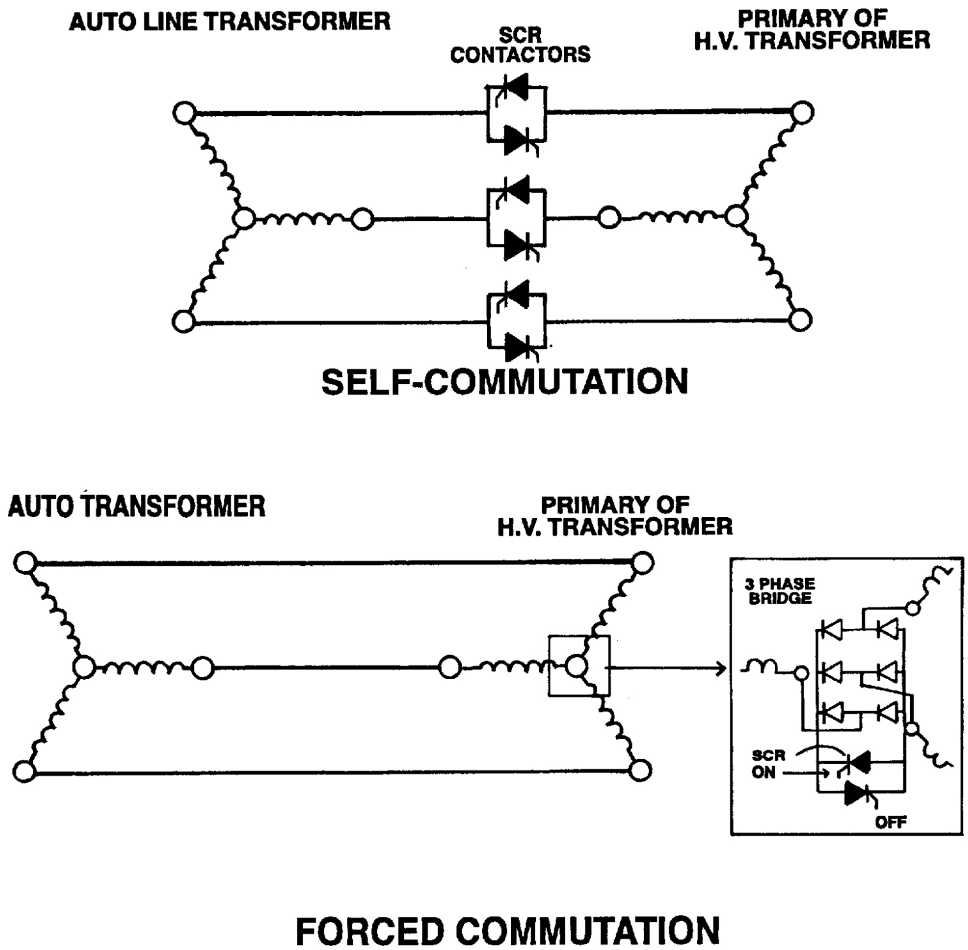

Figure 10. Self-commutation vs. forced commutation. (Top): Notice that two line phases must be switched on for current to flow. (Bottom): One contactor, located at the midpoint of the primary winding of the high voltage transformer, controls current flow.

quently, starting the next exposure with the correct (opposite) alternation. Historically, this has been a function of the time control circuitry. With the closed loop feedback employed in high-frequency generators, the current is closely monitored in the primary and secondary of the high voltage transformer to ensure that saturation does not occur.

Other X-ray Control Functions

The x-ray control has additional features to ensure safe operation and accurate exposure control. After all, the control is where the x-ray

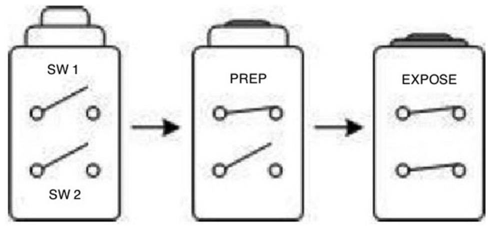

Figure 11. The exposure handswitch. Two commands, prep and expose, are needed to make an exposure. SW-1 (prep) initiates the exposure sequence and remains closed while SW-2 (expose) signals radiation production to begin.

technician (the equipment operator) interfaces with the x-ray system. He or she will select the mode of operation, activate the image receptor, set the proper exposure techniques, and initiate the exposure. Technologists must also monitor the status of the x-ray system, especially the x-ray tube , checking fault indicators and alarms. The service engineer should be familiar the operation of the x-ray control to effectively service the equipment.

The exposure handswitch, an essential component of most x-ray controls, is used to initiate the exposure. Many x-ray units use push buttons on the control console to start the exposure, but even these units may have a second exposure handswitch as a backup. The exposure handswitch is a two-stage pushbutton switch attached to a long (e.g., 3 meters), coiled cable that is connected to the x-ray control. As a requirement, two commands are needed to make an exposure (see Figure 11).

Historically, the design of the exposure handswitch was based on several safety concepts. The type of switch used is termed a "deadman" switch, the name based on the idea that if the x-ray machine operator were to drop dead at any moment during an exposure, x-ray radiation would terminate immediately. The pushbutton actuators on all x-ray handswitches are spring-loaded, and the micro-switches are the momentary action type so that if not actively pressing on the buttons there cannot be an exposure. Similarly, if the operator releases the pushbutton for any reason, the exposure will stop immediately. To get an x-ray exposure, two separate micro switches must be activated: the prep (preparation) and the expose switch. Stated another way, both the prep command (first position) and expose command (second position) must be actived during the entire exposure. This design requires a deliberate act by the operator and is required in all x-ray systems.

The first position of the handswitch initiates the preparatory, or prep command. The prep phase serves many functions in x-ray control. Primarily, it signals the generator to get the x-ray tube ready for an exposure. Functions accomplished during prep include heating the filaments to the proper temperature for the technique chosen by the technologist. With most generators, the filaments are held in a "standby" condition with minimal current running through the filament wires. This practice allows the filaments to be somewhat warmed-up so that the fine wires of the filament will not be shocked when superheated during the exposure. Some x-ray systems do not use a standby or idle current. The thinking is that an x-ray tube, which can remain powered on for many shifts in a day, will have shortened life just because there is current, albeit low, continuously passing through the filaments. Some manufacturers prefer the filaments circuits to remain off until the prep command is initiated. At prep the filaments are heated with a slightly lower voltage initially, then ramped up to the correct voltage required. Both designs work. With simpler x-ray tube applications, like mobile x-ray, it just makes sense to not use the filament standby mode of operation.

A second function of the prep phase is to provide time for the x-ray operator (the x-ray technologist) to prepare the patient for the exposure. During prep the operator verifies proper positioning of the patient, asks the patient to ready for the x-ray by remaining motionless, holding their breath, or exhaling depending on the examination. This very important part of the x-ray examination will ensure a good quality x-ray image. Patient motion is a major cause of poor image quality.

Once the prep phase is completed the operator depresses the second stage of the exposure handswitch. Now, radiation is produced during this exposure phase. The operator holds the pushbuttons down for the entire time as set on the control. If he or she releases at any time, the exposure is terminated.

As stated above, the exposure handswitch has traditionally been attached to the x-ray control console by a coiled tether cable, ranging from a few feet to as much as 20 feet, depending on the type of x-ray unit. Portable x-ray units, where the operator is not usually standing behind a lead shield, require the longer tether cables to allow the operator to step back as far as possible while exposing the patient. X-ray systems found in fixed clinics and hospitals usually have a shorter cable so that the operator must remain behind the permanently fixed lead wall or radiation shield. Some mammography units employ two separate pushbuttons located on either side of the control console that force the operator to stay behind the lead glass viewing window during the exposure. As a rule, x-ray service engineers inspect the exposure handswitch on every PM. These devices can have a high failure rate, especially in mobile and portable applications.

The generator control also provides several additional key functions. To ensure safe operation of the x-ray tube, all generators are equipped with tube protection circuitry. In the most basic generator designs, tube protector circuits will prevent the operator from selecting a technique that exceeds the safe operating limits of the x-ray tube. In this case, when a technique is selected that exceeds the tube limitations, an "exposure hold" condition is created accompanied by a visual "technique over" indication on the console. The technician must reduce the technique settings on the ray control before an exposure will be allowed.

Microprocessor-controlled units can display an error message if a technique exceeds the tube ratings. In addition, microprocessor-controlled units will usually have other special features such as a heat unit calculator that displays the amount of heat units available for use, or a tube loading indicator that displays the percentage of the tube's maximum output that is being used for a given technique.

At installation, the service engineer will program the generator with the exact tube specifications. Some generators provide preinstalled software that contains data on the specifications of the most commonly used x-ray tubes. This software is preprogrammed at the factory so that during the installation the engineer will simply enter a service mode from the console and select the appropriate tube.

Many x-ray applications utilize smaller, lower-power-rated x-ray tubes that contain a stationary anode. These tubes, however, are mostly used in Dental, Pediatric, Mammography, and Mobile settings. Most general radiographic rooms have an x-ray tube with a rotating anode design. Depending on the design and application, there can be a low-speed starter (standard use) or high-speed starter (special applications). Because low-speed starters are relatively smaller in size, they are always located within the x-ray generator control cabinet. On the other hand, high-speed starters are physically larger and are mounted in a separate equipment cabinet. Both high- and low-speed rotor controllers must provide: (1) the proper starting voltage to initiate anode rotation; (2) a means to adjust the "boost" time that the starting voltage will be applied to the stator windings; (3) a lower running voltages to maintain anode rotation; (4) the proper phase shift capacitor for the tube that is being used; and (5) an exposure interlock circuit to ensure that the tube is rotating before an exposure can be attempted.

An AEC unit (automatic exposure control), optionally available with most x-ray generators, is also located in the generator control. When properly calibrated, the AEC will control the exposure time by sensing the radiation that passes through the patient and terminating the exposure when the correct density is achieved. Automatic exposure control is a much more efficient way to obtain consistent x-ray images, consequently, many radiologists request this option.

All generators also provide safety circuits that are required. The operator will monitor the fault status of the equipment while standing at the x-ray control. MA metering circuits are usually connected at the midpoint of the secondary of the high voltage transformer. The midpoint, usually referred to as Ml, M2, is referenced to ground and provides a convenient point to safely monitor the actual x-ray current flowing through the tube. The analog mA meter on the front panel of many generators is connected in series to this point, and this is also the point where an external mA/mAs meter is installed during calibrations. Digital units employ feedback loops, sending the information to a display at the console.

THE HIGH VOLTAGE TRANSFORMER UNIT

As stated earlier in this chapter, the filament wires of the x-ray tube must be heated to liberate the electrons used for x-ray production. A low voltage, regulated power source, in the range of 6-12 VAC, applied to the filaments located in the cathode of the x-ray tube, provides this heating. Also, a high voltage source in the range of 40 kilovolts to 150 kilovolts is needed to accelerate the electrons with sufficient speed so that when they collide with the target, x-rays will be produced. Both the filament transformer and the high voltage transformer are mounted in the high voltage transformer unit. These transformers are completely immersed in insulating oil.[4]

Other components located in the high voltage transformer unit include the high voltage "stick" rectifiers (originally valve tubes in early vintage units) and the high voltage receptacles. The stick rectifiers are a series of diodes mounted (traditionally) on an insulated platform in the size and shape of a yardstick (hence the name "stick"). These high voltage rectifying diodes take the high voltage AC signal from the secondary of the transformer and convert it to a DC waveform. The stick rectifiers necessarily must be insulated in oil. The high voltage receptacles are not only well insulated internally but also are submerged in the transformer tank so that the terminal connections are surrounded by oil. Some transformer units provide additional sets of receptacles for energizing two or more x-ray tubes. These wells are activated by a solenoid or a motor-driven switch which is also located in the transformer unit.

If kVp and mA feedback signals are provided with the x-ray generator, the feedback detection circuitry is located within the transformer unit. Also, there are convenient test points to monitor the primary filament current termed, XL for large focus, XS for small focus, and XC for common located on the top of the transformer unit.

THE X-RAY TUBE

The production of x-ray radiation occurs inside the x-ray tube. There are many different types of medical x-ray tubes available designed for applications such as dental, podiatry, mobile x-ray, and catheterization labs, for just a few examples. The different tubes vary in anode construction, focal spot size, maximum heat capacities, inherent filtration, and tube housing style. Each type of x-ray tube must be correctly matched to the specific radiographic equipment being used and for the intended clinical use. The service engineer should, therefore, be familiar with the characteristics of the various types of x-ray tubes so that he or she can properly advise the radiology administrator or the

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4. Since the secondary of the filament transformer is directly connected to the cathode of the ray tube, it is at a high potential and therefore must be insulated.

equipment dealer as to which tube would be the best choice for the intended application.

As noted earlier, x-ray production occurs when electrons, emanating from the cathode filaments, accelerate towards the anode, collide with the target material, and release radiation. X-ray tubes are designed with either a stationary anode or a rotating anode. A stationary anode is constructed of a copper stem onto which the target is mounted. Copper is used because of its ability to dissipate heat as it accumulates on the target during an exposure. Because the anode remains stationary during the exposure, the stream of electrons emanating from the filament will impact the target at only one area (or focus) of the target. Stationary anode design uses fewer internal components so this type of x-ray tube is smaller, much lighter, and cost significantly less to manufacture. These qualities make them ideal for mobile x-ray applications. They are also used for Dental and Podiatry x-ray applications. When used in these applications stationary anode x-ray tubes perform quite well.

However, an x-ray tube with a stationary anode should not be used in settings that have extremely high patient volumes, such as in major hospitals, or where high power techniques are needed. These applications can introduce excessive heat to the stationary anode that will result in a shortened anode life, and a noticeable increase in effective focal spot size during the life of the tube. This is due to the high flow of electrons hitting one spot (focus) on the fixed anode that will gradually wear away the target material at the focus.

Rotating anodes are preferred in high-use areas because of their greater heat capacity, higher radiation output, and longer target life. One reason for the higher output capacity is because, as the anode rotates the electron beam now impacts an area along the entire surface of the target. This circular "track" of impact is referred to as the focal track. Since the heat is dissipated over a greater surface area, much higher technique factors can be used without the threat of damaging the anode. These tubes can handle high patient volumes.

Rotating anode tubes are, however, more expensive to manufacture because of the special construction and additional components required to produce anode rotation. To achieve rotation, a single-phase induction motor is used. This induction motor consists of a rotating part called the rotor and a series of stationary electromagnets (or field windings) that are together referred to as the stator. The target is directly attached to the rotor.

The stator in all x-ray tubes utilize what is termed a split phase configuration to achieve rotation (Figure 12). This type of stator requires a capacitor to be placed in series with one of the three stator windings (referred to as the "start" or phase-shift winding). The capacitor causes a phase shift to occur between the main and phase winding leading from the single-phase power supply, effectively creating the two-phase supply required to initiate rotation.

The induction motors used in x-ray tubes vary in design among manufacturers, and can be distinguished by the number of field windings used. The service engineer can measure the impedance of the stator windings to determine what type of stator is being used. The three most common types of stators used are the R (or standard), Q (or low impedance), and E (or balanced) stators (see Appendix E).

The rotation of the anode is controlled by the rotor controller or starter, located in the x-ray control (low speed) or in a separate cabinet (high speed) located in the radiographic room. The starter is sim-

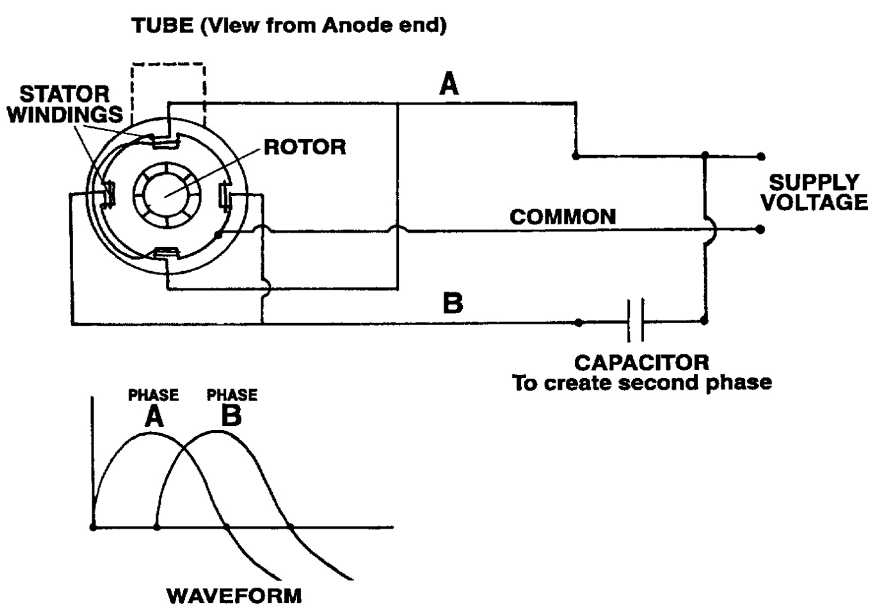

Figure 12. Split-phase stator configuration. The capacitor used to create the two-phase supply is physically located in the rotor controller.

ply a single-phase AC motor control unit that (1) initiates and (2) maintains rotation of the anode. There are two types of starters: low-speed starters and high-speed starters

A low-speed starter will induce an anode rotational speed of 3,300 rpm's and is mostly used for general radiography applications. High-speed starters can induce a rotation of 10,000 rpm's and are used in applications where high x-ray exposure techniques are needed (i.e., angiography). Using an x-ray tube in high-speed mode will allow for a greater accumulation of anode heat which, in turn, increases the output ratings of the tube.

The starter controls the speed of anode rotation by first applying a starting voltage to the stator windings for a set period, called boost time, and then switching to a lower running voltage for the remainder of the exposure. The starting or boosting voltage will quickly get the rotor up to the correct speed and the running voltage will maintain that optimum speed. The values for the start and run voltages are adjusted during the installation. The boost time is adjusted on all rotor controllers to account for anode weight and bearing condition.

In addition to initiating and maintaining anode rotation, the rotor controller also must provide an exposure interlock circuit. This interlock circuit detects the rotation of the anode and then sends an exposure release signal to the generator to allow the exposure to occur. Because of their design, rotating anodes cannot withstand the impacts at one single point along the focal track, but instead must be impacted evenly along the entire focal track thus dissipating the heat over the target. If the rotor controller fails to rotate the anode, the target will be bombarded with electrons at one point on the focal track and will destroy (melt or crack) the target at that point and the tube must be replaced. Most exposure interlock circuits utilize current sensing circuits that operate in a similar manner. As the anode rotates, the current passing through one of the stator leads is sensed by the winding of a special (current sensing) transformer. This transformer then outputs a "rotor ready" confirmation signal to the exposure control logic of the generator to allow the exposure to proceed.

The area of the anode where x-ray production occurs is called the target. The target is constructed of tungsten, rhenium, graphite, molybdenum, or a combination of these materials. These metals are used because of their high melting points and high atomic numbers.

The higher the atomic number, the more efficient the target becomes in producing x-rays.

The diameter of the target is an important consideration in x-ray tube design. As compared with a three-inch target, a larger diameter target of four inches will have as much as 30 percent higher heat capacity and therefore higher exposure techniques can be used. The improved heat ratings can be attributed to the larger focal track which helps dissipate the heat. Anode heat ratings are specified in Heat Units, or HU for short. For single phase units, one heat unit is equal to (1 kVp) x (1 mA) x (1 second). The heat unit was chosen as the unit of measurement because it is much easier to work with than the conventional watt-second. Typical anode heat ratings for general radiographic x-ray tubes range from 300,000 to 400,000 HU.

The target angle of the anode will determine the size of x-ray field coverage, will affect the heat rating of the tube, and influences the effective focal spot size of the x-ray tube. A smaller target angle will produce a smaller effective focal spot size but with reduced image area (see Appendix D). Also, a smaller target angle will allow greater short-time exposure ratings of the tube.

A larger target angle, on the other hand, will increase the x-ray field coverage, produce a larger effective focal spot size, and will reduce the exposure rating of the tube. The goal when selecting an x-ray tube is to choose a minimum target angle that will achieve the image area desired.

Heel effect is a phenomenon of x-ray tubes that must also be taken into consideration when selecting a target angle. Heel effect is defined as the variation in exposure rate with the angle of emission of the radiation from the focus. Figure 13 demonstrates that the radiation gradually decreases in energy in the direction towards the anode. This is due to the greater attenuation of the x-rays as they pass through the thickness of the anodes "heel." A smaller target angle produces more heel effect.

The engineer will compensate for the heel effect during the installation by mounting the x-ray tube in an orientation (in respect to the image receptor) that minimizes the heel effect. As a rule, the anode is usually located at the head end of the table or receptor.

The focal spot size of the x-ray tube must also be considered when choosing an x-ray tube. The focus of the tube, or effective focal spot size, is directly related to the size of the filament wire and, as men-

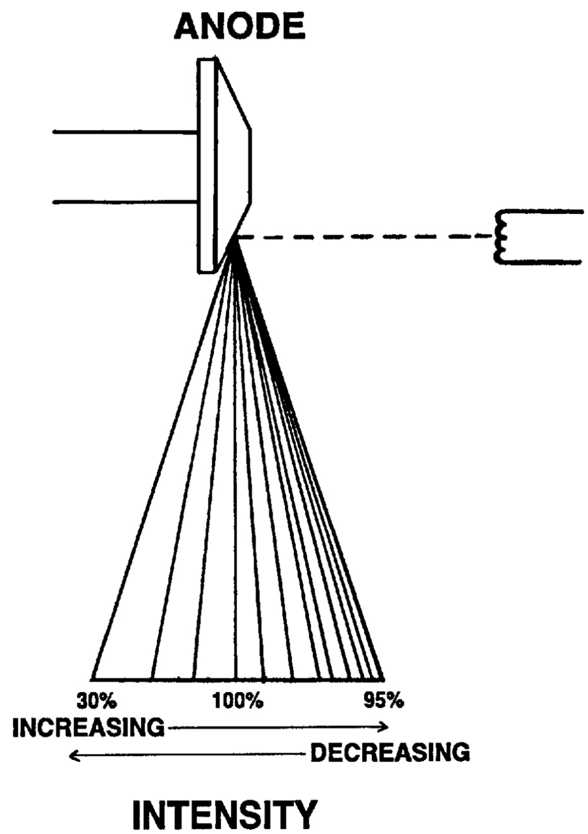

Figure 13. The heel effect. The x-ray beam is attenuated as it passes through the thickness of the target material.

tioned earlier, the target angle. Most of the x-ray tubes manufactured today are dual focus tubes which provide both a small and large focal spot.

For general radiography, the small focus of the x-ray tube measures in the range from 0.6 mm to 1.0 mm, whereas the large focal spot size ranges from 1.0 mm to 2.0 mm. For applications requiring fine detailed imaging (e.g., vascular imaging), smaller focal spot sizes are used. The smallest focal spot sizes used in radiography are used in mammography, with 0.1 mm/0.3 mm focus being the most common focal spot combination. The drawbacks of using a smaller focal spot size, however, are that the overall heat ratings of the tube and short-time exposure ratings are significantly reduced.

Another important consideration in regards to x-ray tubes is the x-ray tube housing. The tube housing, made of metal, contains the glass insert surrounded by insulating oil. The heating and cooling ratings of the tube housing are directly determined by the type and size of housing. These ratings, usually given in graphic form, show the maximum heat accumulation allowed per unit of time for that housing. From the graphs and charts that are always included in the information packet that came with the tube, the engineer can determine how quickly the housing can dissipate heat. Typical values for heat storage capacities for housings used in general radiography are rated well over a million heat units.

The heating/cooling ratings are not only dependent on the size of the housing, but also by the method of cooling that is employed. X-ray tubes can be air-cooled (with or without an external fan), oil-cooled, and even water-cooled. Air-cooled tubes are most commonly used for general radiographic applications. Many air-cooled tubes are equipped with an air circulator (i.e., box fan) which greatly increases the heat rating of the tube housing. Oil- and water-cooled tubes have even greater heat capacities and, consequently, are used for high technique applications. The oil (or water) in the housing is circulated by a pump to a remote heat exchanger where it is cooled and then recirculated to the tube through hoses.

Another consideration to keep in mind when choosing the type of tube housing to be used at a facility relates to the horn angle. The horn angle describes the relationship of the tube port, where the x-ray beam exits, to the tube high voltage receptacles, or "horns." The horn angle for a tube is measured in [radian] degrees. For example, a housing with a 0° horn angle will have both the high voltage receptacles and the tube port facing in the same direction; a 180° horn angle will have the high voltage receptacles pointing in the exact opposite direction of the tube port. The horn angle must be correct so that the anode will be oriented correctly, and so the cables can be properly hung. For convenience, the standard horn angle designations are listed in Appendix C.

The final consideration with regards to tube housing type pertains to how the x-ray tube will attach to the tube supporting device. The x-ray tube can be mounted directly to the tube support by means of four bolts. These mounting bolts are directly threaded through the tube mounting plate of the tube support and then into the tube housing.

Another way of mounting an x-ray tube is by using a trunnion mount. In this second type of tube mount, the x-ray tube housing is not bolted directly to the tube support. Instead, trunnion rings wrap around the tube housing and hold the tube in place. Most trunnion ring mounts have a tension adjustment knob that can be loosened so that the technician can rotate the tube for special radiographic views.

THE HIGH VOLTAGE CABLES

The high voltage transformer unit is connected to the x-ray tube via the high voltage cables, sometimes called the high-tension cables. Both ends of the high voltage cable are terminated with a special type of connector, termed a federal connector (Figure 14). Federal connectors are used because of their insulating capabilities with regards to the very high voltages used in radiography. The design of these connectors creates a gap of several inches or more between any high voltage point and ground. They plug directly into sockets, or wells, located on top of the transformer and into x-ray tube housing. The ends of the cables are coated with a petroleum-based, dielectric compound (vapor proofing compound) and then inserted into the tube or transformer. Often the insulating oil that is used inside the transformer is added to the high voltage transformer wells instead of the vapor proofing compound to prevent arcing.

Two important components of the federal connector are the grounding compression washer and the rubber gasket. The grounding washer must be used in the x-ray tube and transformer receptacles to ensure that the high voltage cables are safely grounded. The rubber gasket is needed to provide the proper spacing in the high voltage receptacle and to seal out moisture.

Because of their construction, the high-tension cables add a specific amount of capacitance to the high voltage circuit. The amount of capacitance is determined by the cable construction and by the length of the cables. The increase in capacitance has a filtering effect on the high voltage waveform and must, therefore, be accounted for during calibration.

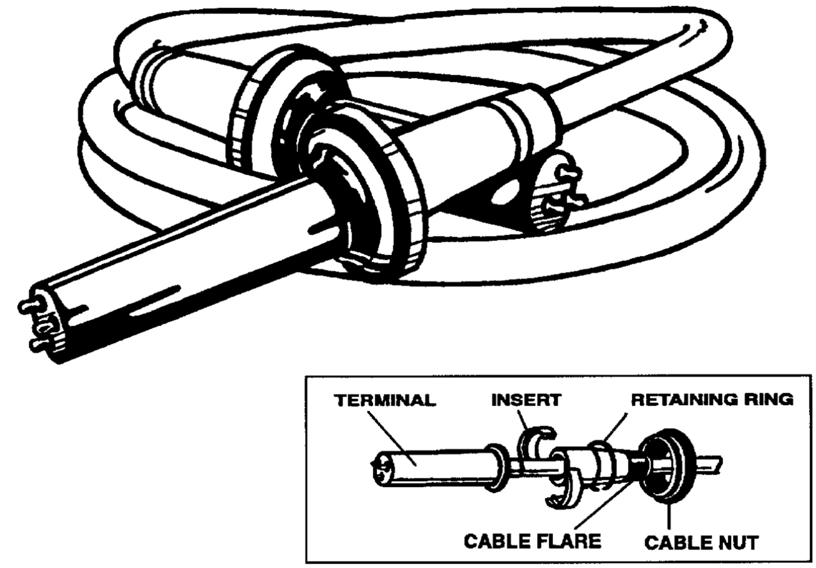

Figure 14. High voltage cable with federal connector.

Chapter IV

THE GENERAL RADIOGRAPHIC ROOM

The general radiographic room has been in existence for more than 100 years and is the most common type of room used today for diagnostic x-ray examinations. The same devices that were used in those early x-ray rooms are still regularly being employed in today's hospitals and clinics. Again, the basics of x-ray have not change since its inception.

Besides the x-ray generating equipment described earlier, other devices are needed in the general radiographic room to obtain a good diagnostic quality image of patient anatomy. A tube support is needed to position the tube so that it can be directed to the specific anatomy to be imaged, holding it firmly in place during the x-ray exposure. An image receptor is needed to convert the radiation energy that is exiting from the patient to a permanent visible image. A radiographic table has unique qualities that allow technologist to do a variety of examinations.

Finally, a collimator is required in all radiographic rooms. The collimator is an essential safety device that is used to reduce the size of the radiation field to the area of interest, thereby reducing scatter radiation. Scatter radiation is not only harmful to the patient and hospital staff, but also causes a reduction in image quality (see Chapter V). Collimators also provide a visual light field that accurately defines the x-ray field, so that the technologist can precisely align the patient.

THE TUBE SUPPORT

The function of the tube support is to provide accurate positioning of the x-ray tube. The two tube supports commonly used in a radi-

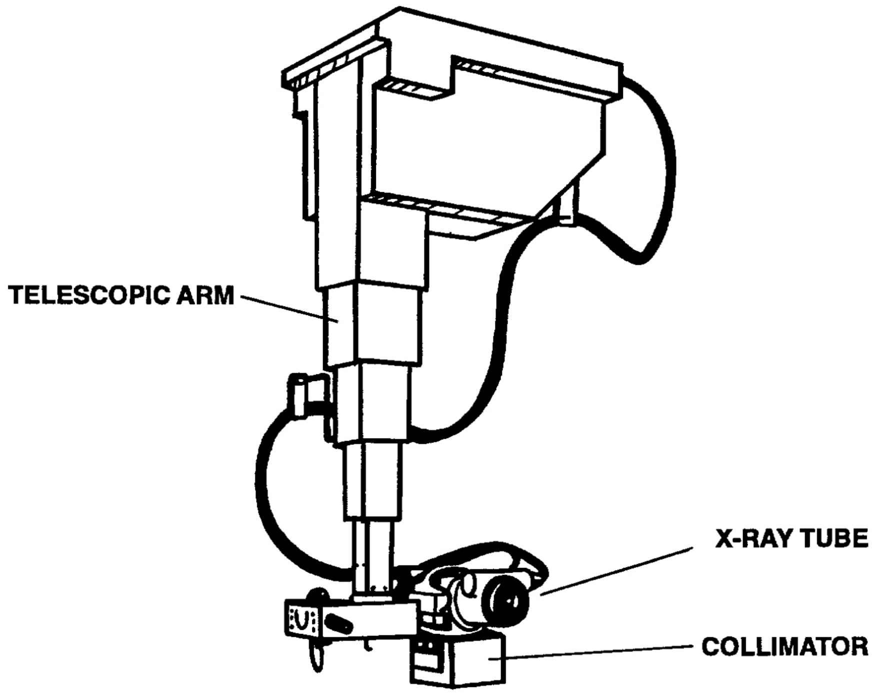

Figure 15. The overhead tubecrane. A tube support system.

ographic room are the overhead tubecrane (Figure 15) and the tubestand (Figure 16). The overhead tubecrane is mounted to rails that attach directly to ceiling supports.

The tubecrane moves along the ceiling rails to position the x-ray tube for the desired anatomical view. A tubestand is usually mounted on a track that runs along the floor and one that runs along the ceiling, but can also be mounted from the floor to a track mounted on the wall. Some tubestands are mounted directly to the x-ray table.

An integrated tubestand, sometimes referred to as a U-arm, was designed for installations where the size of the room severely limits the use of a separate tube support and image receptor (Figure 17). With the integrated tubestand, the tube support and the receptor are both attached to a single support column. These integrated units are easy to install, occupy very little space in the room, and can provide most of the radiographic views required for x-ray examinations.

Regardless of the type of tube support, its main function is to hold the x-ray tube at an angle, height, and rotation that are needed for the

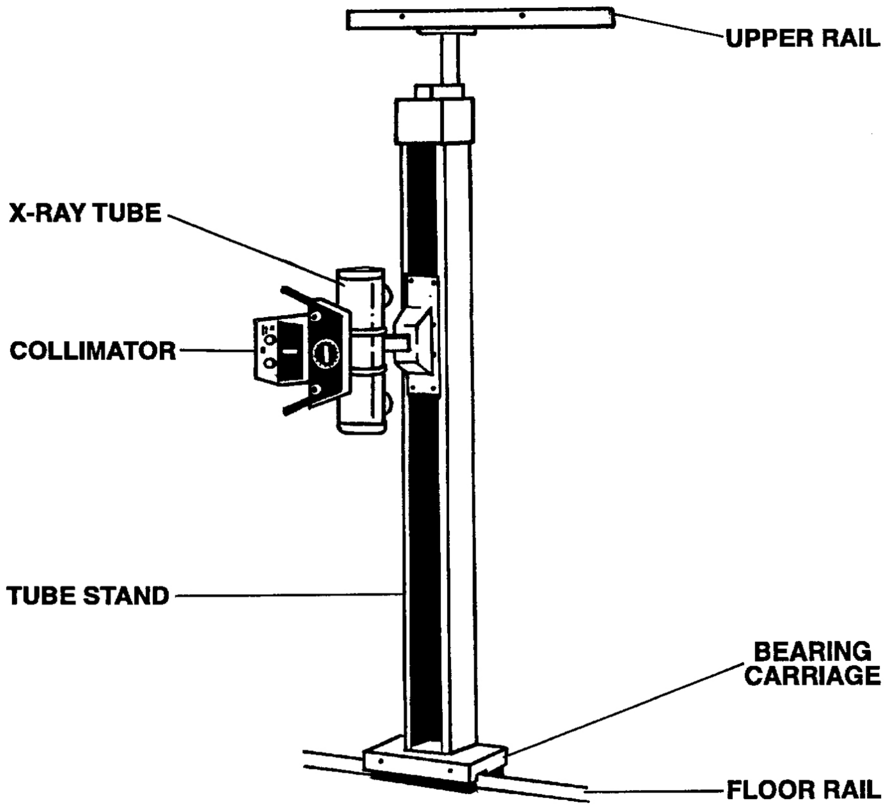

Figure 16. The tubestand. A tube support system.

x-ray examination being performed. Most tube supports use electromagnetic locks to hold the tube in the desired position. The most basic tube support designs can have friction locks. The tube support must move smoothly in all directions. However, because of the weight of the x-ray tube, all tube supports require a counterbalancing system to accomplish smooth, effortless movement in the vertical direction.

The counterbalancing system includes pulleys, cables, and either counterweights or a spring tension (i.e., counterpoise) mechanism. Some tube supports can provide motorized movement. Additional features that may also be included in a tube support are an SID (source to image distance) indicator and a tube angulation/rotation indicator.

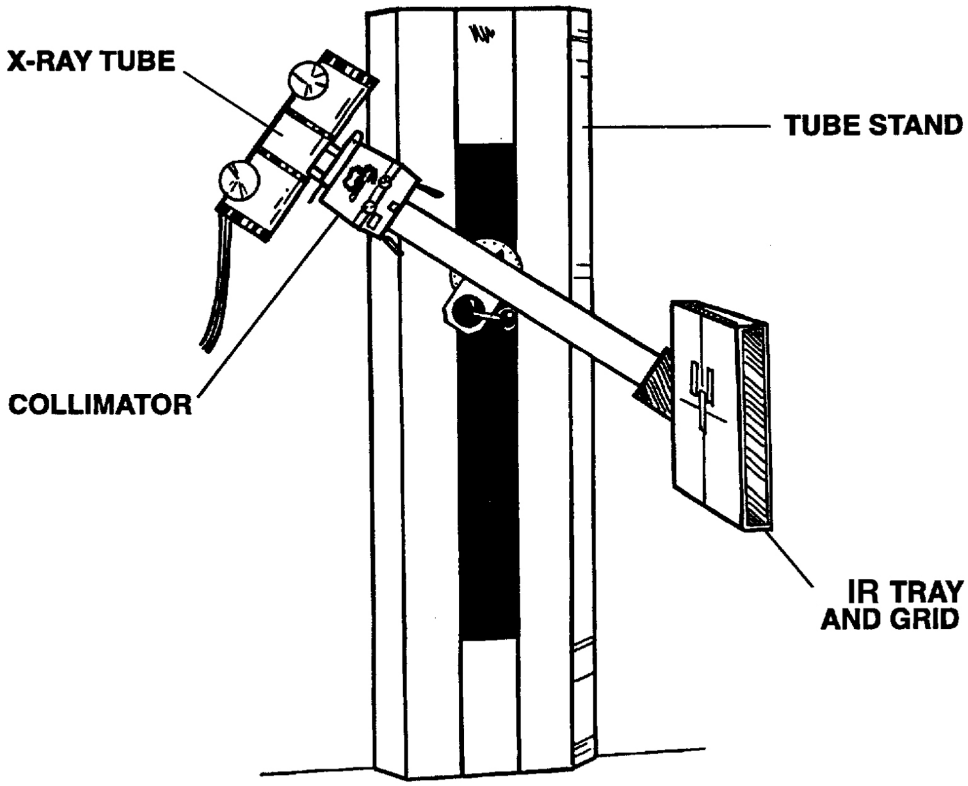

Figure 17. The integrated tubestand. The integrated tubestand positions both the x-ray tube and image receptor.

THE IMAGE RECEPTOR

The image receptor (or IR) is the device that creates and processes the image of the patient's internal anatomy. Specifically, the image receptor, located directly behind the patient, is where x-rays exiting the patient create an image either by converting x-ray radiation to light radiation (indirect method), or by directly exposing the IR (direct method). The IR sends the digital image to be further processed and then permanently stored. Image receptors can be of many types, depending on the technology being used. When film was used, the IR was comprised of the film, film cassette, cassette holder, and a grid–all of which are contained within an enclosed cabinet (Figure 18).

Digital technology can use the same grid cabinets found in the original x-ray rooms, but replaces the film cassette with either a CR

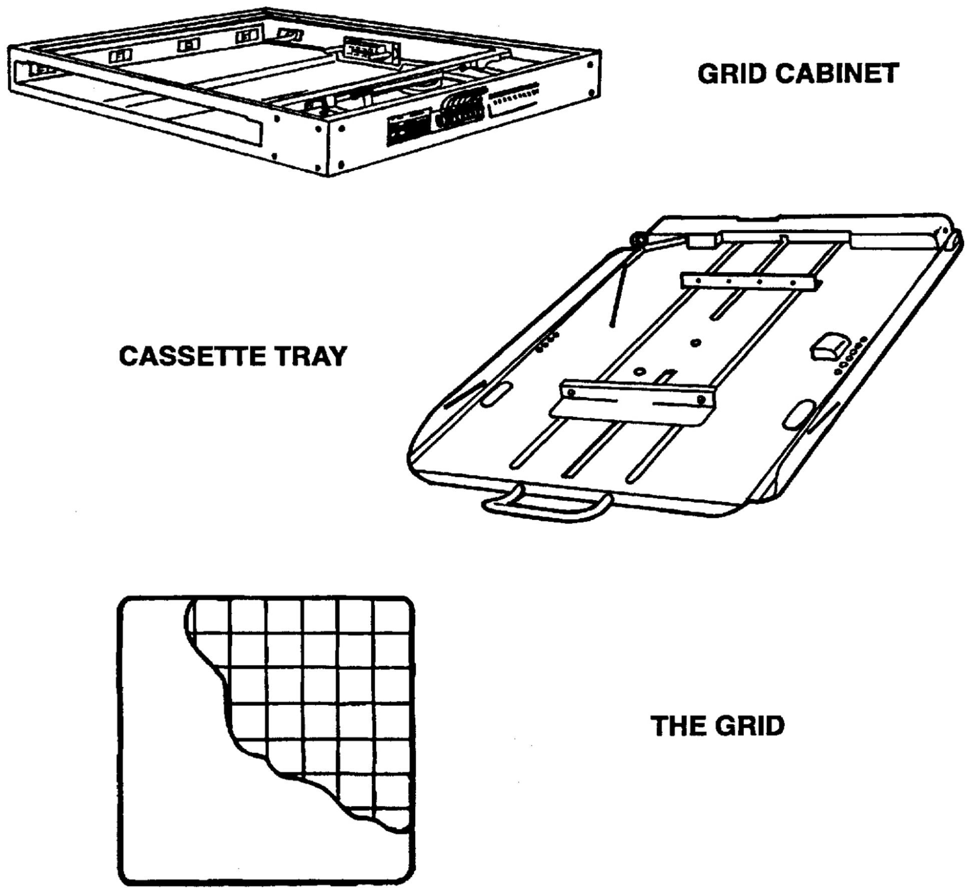

Figure 18. The image receptor. The grid and cassette tray are located within the grid cabinet.

cassette or DR panel, making upgrades to digital receptors a seamless operation. CR technology utilizes intensifying screen cassettes like those used in film cassettes but in place of film, CR uses an imaging media to record the image. The imaging media is exposed and then later read on a CR scanner (or reader). With DR technology, the DR panel fits into the cassette tray and when exposed creates a digital image ready for viewing. Image receptors are located either on the wall for erect studies, or located inside the x-ray table for studies where the patient must lie in the prone position.

All receptors cabinets allow for the placement of an x-ray grid. Grids are constructed of lead strips separated by an interspace material such as wood or aluminum. X-ray grids, when positioned in front of the image media, allow the primary x-ray beam to pass through while blocking any scatter radiation traveling at angles to the image plane. Grids are used to reduce scatter radiation and thereby greatly improves image quality (see Chapter V).

Grids can be removable, or permanently mounted in the receptor enclosure. A stationary grid is positioned in front of the cassette tray in a grid cabinet. If the grid is a reciprocating (or oscillating) type, the grid cabinet is then termed a Bucky.[5] A reciprocating grid provides more scatter reduction than a stationary type and, therefore, greatly improves image quality. If an optional automatic exposure control (AEC) device is used, it is also placed in the grid cabinet or Bucky assembly.

The cassette holder, another type of image receptor assembly, is a more basic design that does not enclose the cassette in a cabinet. It has an upper and lower jaw that locks the cassette (or DR panel) into position. The cassette holder assembly is usually mounted directly to the wall and can move vertically along a track. A slot is also provided in front of the cassette holder to accommodate a removable stationary grid.

THE RADIOGRAPHIC TABLE

A radiographic table (Figure 19) is a specially designed table used for x-ray examinations. The table has several distinguishing features that ensure that the technologist will obtain a good quality image of patient anatomy. All radiographic tables must have a tabletop made of a special material that will allow x-ray radiation to pass through unimpeded. Technically speaking, a tabletop must have a high transmission and low absorption characteristics. The material in the tabletop must also have a uniform density and must be free of defects that could cause artifacts on the image. The tabletop must also be strong enough to support the weight of patients. Most tables can support a minimum of 300 lbs. upwards to as much as 800 lbs., depending on design. Wood and carbon fiber materials are commonly used in table tops.

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5. The Bucky was originally called the Potter-Bucky Diaphragm, named after Dr. Hollis E. Potter and Dr. Gustav Bucky who invented it in 1920. The named was shortened for convenience and today the "Bucky "is the accepted name for that device.

Another feature of a radiographic x-ray table is that it must contain a mechanical device that will hold the image receptor in place. These devices are commonly termed grid cabinets or image receptor assemblies. The image receptor is placed within a cabinet located directly under the tabletop. Grids, cassette trays, DR panels, and automatic exposure detectors are all contained in the grid cabinet. Most image receptor assemblies slide in a track along the length of the table to image various parts of the anatomy.

Starting from the most basic radiographic tables described above, optional features can be added to improve the functional capabilities of the table. These include: a hi-lo option for mechanically raising and lowering the table height, a floating tabletop option which allows the tabletop to move freely in all directions, and a tilting option that mechanically tilts the table 90 degrees.

THE COLLIMATOR

The other extremely important device found in a general radiographic room is the collimator–a device that plays a vital role in radiation safety. Collimators reduce the radiation field size precisely to the

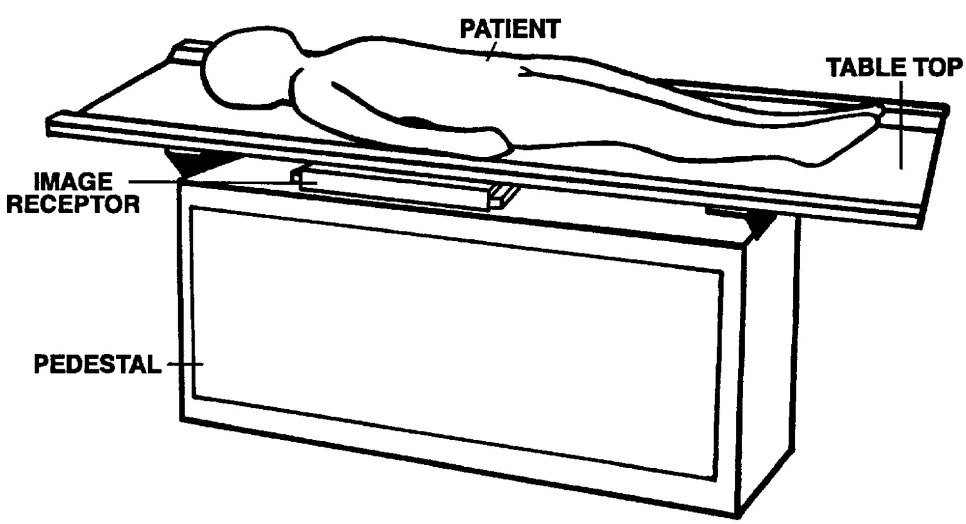

Figure 19. The radiographic table. The image receptor and table top move to facilitate positioning.

specific anatomy that will be imaged. They are categorized as a beam limiting device and serve a very important function in radiography in terms of radiation safety. By limiting the beam to the area of interest, collimators significantly reduce the radiation exposure to the patient. In addition, collimators reduce scatter radiation (discussed later) which also limits radiation exposure to the technologist and radiologist performing the exam. Because of the safety implications, collimators are tested regularly by state inspectors. The service engineer should take care when repairing and adjusting these special devices.

Collimators are, by far, the most common type of beam-limiting device found in radiography because they can vary the x-ray field size by moving two sets of mechanical shutters made of lead–one set limits the field in the longitudinal direction, the other in the transverse direction. They have replaced the use of cones and diaphragms, which were commonly used in early radiographic rooms.

The two sets of lead shutters are positioned at right angles in such a way as to form a rectangular field (see Figure 20). Collimator fingers are attached to the upper set of shutter blades and function to eliminate off-focus radiation (or stem radiation). Another type of collimator uses an adjustable circular shutter (or diaphragm) and is normally used in conjunction with an image intensifier. All collimators also provide a slot into which additional filters may be added to modify the x-ray beam.

A second important function of a collimator is to provide a light field that precisely represents the x-ray field. The light field aids the x-ray technician in positioning the patient. For radiography, the collimator light field must match the x-ray field to within 2 percent (commonly) of the SID. In addition, a centering light is often present that allows for aligning the x-ray tube with the image receptor.

To produce a light field bright enough to view in normal room lighting, collimators must have a dedicated high current lamp power supply and a special high output lamp. The field lamp must remain powered on long enough for the technologist to position the patient, typically 30 seconds, then automatically shut off. Because of the high current (and high heat) generated in the lamp circuit, all collimators use a lamp timer circuit that will automatically turn off the lamp after the desired time (Figure 21). The lamp timer ensures that the light will turn off at the set time thus avoiding heat damage to the internal com-

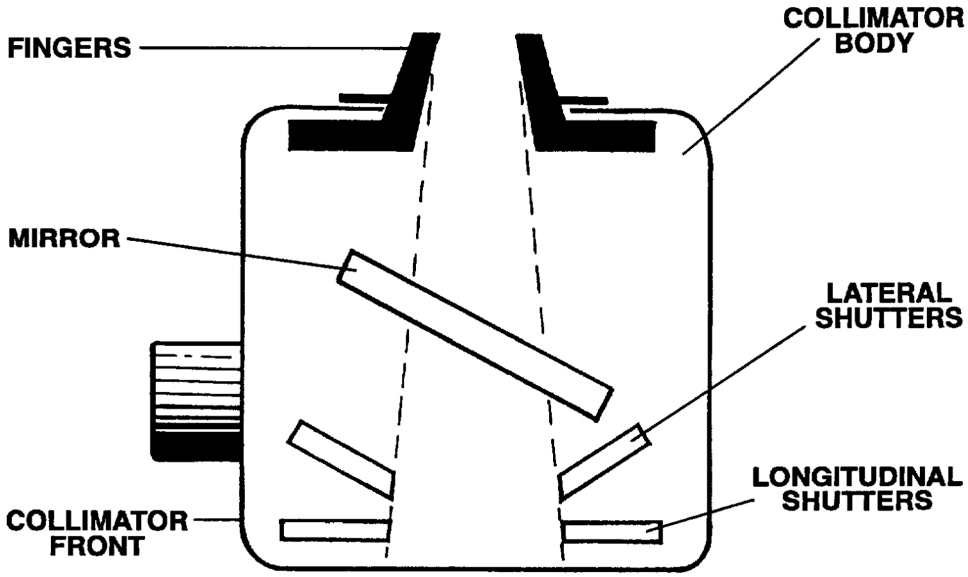

Figure 20. The collimator. The fingers are needed to remove stem radiation. The mirror adds additional filtration to the x-ray beam.

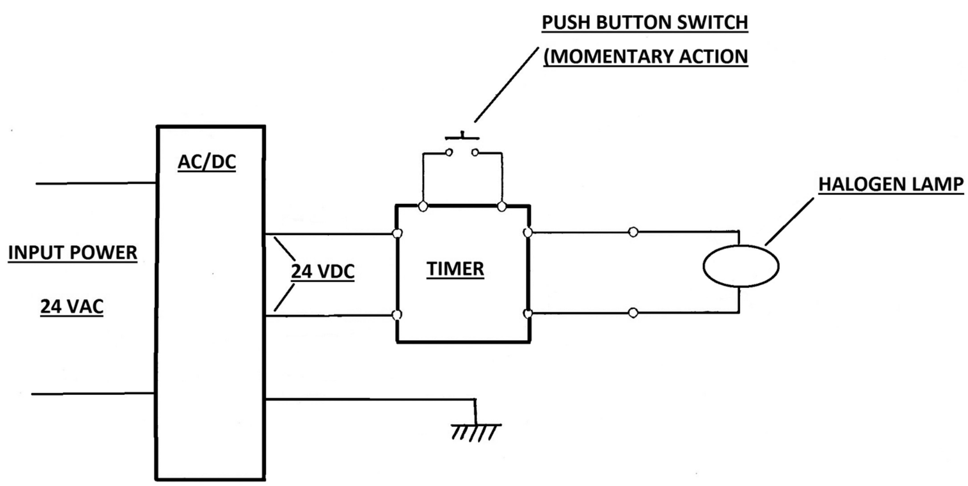

Figure 21. Collimator lamp timer circuit.

ponents of the collimator. These items are contained within the housing of most collimators, although the lamp timer circuitry may be located remotely in a collimator control cabinet.

Shutter Operation

Collimators can be designed for two modes of operation: manual or automatic. Manual collimators are more basic in design, requiring no additional circuitry other than what was described above. To adjust the field size, the x-ray technician energizes the collimator lamp and manually turns the transverse and lateral shutter knobs to the desired field size. Collimator field size indicators are attached to the knobs so that the technologist can set the shutters to a specific field size: 10 inch by 12 inch, for example. These collimators work perfectly well and are ideal in portable applications where weight is a consideration.

Automatic collimators, on the other hand, contain the additional circuitry needed to drive the shutters automatically to the correct field size once a cassette or DR panel is inserted. This additional circuitry consists of DC motors which open and close the shutters, as well as some type of control logic to tell the motors when to drive and for what duration. This automatic mode of operation is sometimes referred to as PBL (Positive Beam Limitation) by some manufactures.

Also, automatic collimators have an exposure interlock circuit which is designed to inhibit exposures if certain criteria are not met. The receptor must be present, for example, and the SID must be correct to release the interlock and allow the exposure to occur. A semiautomatic collimator, also available from most manufacturers, employs all the logic control of an automatic collimator, but without the drive motors to save cost. The shutter knobs are turned manually until a "ready" light appears on the collimator.

In the event of a failure, all automatic collimators provide a bypass switch located either on the collimator or in the remote collimator control panel. This switch is used to bypass the automatic mode of operation. By enabling this switch, the operator switches the collimator from automatic mode to manual mode. The collimator can be used in this mode until the service technician arrives to repair the automatic circuitry.

Chapter V

IMAGE QUALITY

In the field of x-ray servicing, each alignment and calibration procedure is performed with one goal in mind: optimum image quality. After all, the purpose of x-raying a patient is to obtain an image of an internal structure that can be later used for medical diagnoses. The goal of the x-ray service engineer is to fine-tune the x-ray system so that the best possible image can be produced. To intelligently discuss image quality, however, we must define what is meant by a "good image." This chapter will review all the factors affecting image quality and how each device found in a radiographic room influences the quality of the final image. First, a brief historical background of x-ray imaging.

HISTORY: X-RAY FILM

As noted throughout this book, the field of radiography has been historically tied to the use of photographic x-ray film. X-rays passing through the patient produced a "radiograph: a permanent image that was stored on film." In fact, film has been the only permanent storage medium used in radiography up until just very recently. As of the writing of this third edition (year 2016), film is still being used in certain industries such as dentistry, the veterinarian field, and mobile x-ray.

Because general radiography was film-based, image quality was defined by how an image appeared on exposed emulsion film. The type of x-ray film and the film development process were key factors to obtaining a good image. Many types of film were available, ranging from low- to high-speed film, some providing high detail, other film offering reduced background noise. Also, film processing varied greatly. Film was processed at fast and slow speeds, with strong or weak developer, and at different developer temperatures–each of the variables had a significant effect on the final image. The x-ray technologist, working together with the radiologist, would experiment with the different variables to obtain the best possible images for that system. The bottom line: obtaining a good radiograph required special skills that took many years to acquire. In fact, radiography was considered an art, developed by the cooperative effort of radiologist, technologists, equipment manufacturers, and film and film processor companies. Thus, when discussing image quality, it is helpful to look to the past to see how good image quality was obtained. We can then apply those principals to digital imaging.

The important concepts to consider for good image quality are the optical density of the image, image contrast, and image sharpness. A good image should have sufficient optical density so that the internal structures can be clearly seen on the image. Optical density refers to the overall "blackening" of the image and is the most important factor of a quality image. The image must be dark enough so that the all structures of the patient can be clearly seen when viewed on a monitor.

With film, optical density was precisely measured with a densitometer, which can detect very small changes in film density. The densitometer measures film density by passing a light of a certain intensity through a small area of the film and then compares it with the intensity of light that emerges from the film. The film density is equal to the common logarithm of the ratio of the two measured intensities. Mathematically, $D = \log_{10} (I_0 / I_t)$, where I_0 is the original calibrated light intensity and I_t is the intensity of the light transmitted through the film.

The human eye can only distinguish density differences in a very limited range (up to about 2.5D). In fact, at an optical density above 2.5D, the film would be so dark that no specific structures in the image could be distinguished. In addition, at extremely high (or low) densities, the contrast range of the film is significantly reduced (discussed later). Normal film densities ranged from approximately 0.5D to 1.5D.

An image should also have sufficient contrast so that each type of tissue (bone, cartilage, soft tissue, etc.) can easily be discerned. Image contrast refers to the difference in optical density between two adjacent structures on the image. A greater density difference between these adjacent structures will result in higher image contrast. A high contrast image will appear black and white with very few shades of gray. A low contrast image will gradually change from black to white, having many shades of gray in-between.

The optimum contrast level for an image will vary with the type of anatomy being filmed. If the radiologist is interested in viewing bone tissue, an image with high contrast is preferred. When soft tissue is being studied, a lower contrast image is needed to distinguish the various individual structures.

Finally, a good image should have a sufficient detail so that the borders of each structure appear sharp and focused. Image detail refers to how quickly the change in density occurs between two adjacent regions. This directly relates to how sharp the individual structures will appear. A very abrupt change in density between adjacent areas on the image will produce an image with clearly defined sharp edges. When discussing image quality, an image that has structures with clearly defined, sharp edges is said to have good detail. Other terms used interchangeably when referring to image detail are image definition, image resolution, and image sharpness.

In addition to density, contrast, and detail, a good image should precisely represent the actual size and shape of the patient's anatomy and should not "distort" the internal structures of the patient. Image magnification and image distortion can occur when the patient is not properly positioned in the x-ray field. If the image is distorted, a misdiagnosis could result.

Finally, a good image should have minimum background noise. Radiographic noise has a grainy or salt and pepper appearance on the image. The noise is a result of several factors discussed later in this chapter. Radiographic noise only reduces image contrast and will, therefore, greatly deter from image quality.

In a general radiography room, every device in the x-ray system directly influences the quality of the final image that is produced. Each will be discussed in detail in the following pages. Later chapters will cover the procedures used to align and calibrate each radiographic device to achieve an optimum image. This information will aid the service engineer in improving the images produced from an x-ray system. To begin, a brief overview of the image formation process is provided.

IMAGE FORMATION

When discussing image formation, we must consider all aspects of radiography, from the production of x-rays to final image processing. Of all the factors considered, it will be shown that the most important factor in the image formation process is the quality of the x-ray beam itself. To produce a good image, the x-ray radiation emanating from the x-ray tube must be of sufficient energy (or quality) to pass through the patient and onto the imaging medium. Once the proper "beam quality" is achieved, each device in the imaging pathway can only modify that x-ray beam in some way to help produce the final image.

Specifically, to record a diagnostic image of a patient's internal structures, an x-ray beam composed of many energy levels is needed. When this beam strikes the patient, the x-ray photons will interact with the body in three different ways. The highest energy photons will completely penetrate the patient, passing directly through to the image receptor. The remaining photons of lower energy levels will be attenuated in two ways. When striking the tissue, the photons will either be absorbed directly into tissue or they will scatter (i.e., travel in a direction other than that of the primary beam). It is the differential absorption of the x-ray beam that creates the image, so the discussion of image formation will concentrate in this area. Scatter radiation only hinders the image formation process.

The internal structures of the patient will absorb x-ray photons differentially, depending on the density of the tissue. The variation in absorption of the beam will result in a radiation beam exiting the patient that consists of varying intensities. Specifically, the energy level of the x-ray photons in the exit beam will vary per cross-sectional area of the patient. This variation of intensities, known as subject contrast, will form the actual image. Subject contrast determines the amount of image contrast that the final image will have. Once an exit beam with good subject contrast has been created, it now must be converted from radiation energy to light energy so that the human eye can view that image.

With film, the exit beam that emerges from the patient passes through an intensifying screen where it is converted to light which exposes the x-ray film. The intensifying screens and film are contained within a light-tight cassette, which is positioned directly behind the patient. The screens are normally made of phosphor, which is a type of scintillator material used to create luminescence. The intensifying screens not only convert the x-ray photons to light photons but also amplify the light output to efficiently expose the film. The film has a coating of emulsion that has sensitive silver bromide crystals suspended in a gelatinous material. The light energy that hits the emulsion of the film causes the silver bromide crystals to undergo a chemical change resulting in the depositing of neutral silver on the film. The amount of silver that is deposited at each point on the film is directly related to the amount of light that strikes the crystals at that point. The clustering of neutral silver deposits in the emulsion forms an invisible image that is termed the latent image. The crystals that are not exposed to light will remain physically unaltered. The exposed film with the latent image must undergo further processing to make the latent image visible to the human eye. The film is processed in a developer solution that contains more silver ions. The silver ions in the developer react with the neutral silver to form deposits of black metallic silver. The developer has no effect on the unaltered silver bromide crystals. The black silver grains, deposited in the gelatin of the emulsion, form the visible image.

When the film has been fully developed, it must then be placed in another chemical, the fixer, which clears the film of all unaffected silver bromide crystals. If these unaltered crystals were to remain on the film, they would further react with light and, consequently, fog the film. The fixer also hardens the film and makes the image permanent. After the film is washed and then dried, the image formation process is complete and the film is ready for viewing. Fully processed film, if stored properly, will remain in diagnostic condition for many years.

Today, the most common means of creating a visible image is with CR (Computed Radiography) and with DR (Digital Radiography). With CR, the exit beam is converted to light energy first, as with film technology and then further processed digitally. The x-ray radiation is converted to light by the process of scintillation. Here, the high-energy x-ray photons strike a luminescent material and scintillate (i.e., remit the energy in the form of light). Scintillators used with CR are like the intensifying screens used in film cassettes. But rather than exposing film, the scintillator exposes an imaging plate (IP) that stores the image. The imaging plate, made of photostimulable phosphor, will be processed in a "reading device," the CR reader, which has a laser scanner. The CR reader scans the image from the exposed image plate and sends the digitized image to a computer for viewing and interpretation.

With DR flat panels using the indirect detector method, x-ray radiation is also first converted to light energy. The scintillator commonly used is comprised of either Cesium Iodide (CSI) or Gadolinium Oxysulfide (or Gadox). The scintillator is coated over an active matrix array of amorphous silicon (a-Si) photodiodes. The photodiodes detect light and covert it to an electrical signal corresponding to its intensity, which is used to create the image. In DR panels using the direct detector method, a scintillator is not required. The exit radiation directly interacts with the thin-film transistors (TFTs), which are coated with amorphous Selenium (a-Se). The resulting digital signal is further processed to create the image. The main difference between direct and indirect detection in DR technology is that indirect is a two-stage process: (1) x-ray to light conversion, and (2) light to an electrical signal, which results in higher gain but slightly lower resolution.

But the clear advantage of digital radiography relates to reliability, and the convenience of storing and sharing images. Both CR and DR images can be stored remotely and later viewed on a PACS (picture archiving and communication system). PACS enables virtually any radiologist worldwide to view the images for diagnoses. Other advantages to digital radiography include (1) no image degradation over time; (2) lower cost: no need for the costly chemicals used with film and film processing; (3) no need to store film, which takes up significant space at the hospital or clinic; (4) no film processors, which take up an entire room and must constantly be maintained; (5) no hazards related to disposal of chemicals and film. Furthermore, with digital imaging, there is less dose delivered to the patient and fewer retakes due to the wider dynamic range of digital images.

BEAM QUALITY

As stated earlier, the quality of the x-ray beam is fundamental to obtaining good image quality. Beam quality describes the overall energy level of radiation in the x-ray beam which will indicate the penetrating ability of the beam for a given kVp. If the beam consists predominantly of high energy photons, it is considered a “hard” beam. A hard beam will have good penetrating ability since more of the high-energy photons in the beam will pass through the patient unimpeded. Furthermore, if more photons are passing through the patient, fewer photons will be absorbed by the patient.

If the beam consists of lower energy x-ray photons, it is referred to as "soft" radiation. Soft radiation has a lower penetrating ability and is mostly absorbed by the patient. Because the low energy photons are more easily absorbed in tissue, a soft beam will increase subject contrast and for this reason is desirable in special applications of radiography such as mammography, where the visualization of soft tissue is desired.

The three major factors that affect the quality of the x-ray beam are the selected kVp (and associated output waveform), the material used in the anode of the x-ray tube (or anode construction), and the amount of filtration in the x-ray beam. The effects of kVp and anode construction are discussed later in the chapter. Our discussion now concentrates on filtration and its relation to beam quality measurements.

FILTRATION

Filtration is the process of removing unwanted low energy radiation from the x-ray beam. The x-ray beam is filtered by placing thin sheets of homogenous metal, usually aluminum (AL1100), in the path of the beam at a point as close to the x-ray tube as possible, usually at the collimator. Placing the filter this close to the tube effectively blurs out any imperfections (e.g., scratches) in the filter.

The aluminum sheets "filter" the beam by removing the low energy x-ray photons. These low energy photons do not contribute to the image in general radiography and, more importantly, increase the dose delivered to the patient. Using filtration, the penetrating ability of the beam can be increased to achieve optimum imaging and, as a result, the patient will absorb less radiation. And as more filtration is added in the path of the beam, the penetrating ability of the beam will correspondingly increase. Excessive filtration results in an image with extremely high contrast which is not desirable for viewing soft tissue. Again, the most significant drawback with using too little filtration is that the patient absorbed dose will increase.

MEASUREMENT OF BEAM QUALITY

Beam quality is defined in terms of the amount of filtration in the x-ray beam. The measurement of beam quality is called the Half Value Layer or (HVL). The half value layer is defined as the amount of aluminum required to reduce the radiation output of the tube to one-half the original value at given kVp. An important point to remember regarding HVL is that beam quality is very dependent on the kVp used and, accordingly, so is the HVL measurement. Therefore, the kVp setting must always be recorded with the HVL result.

The half value layer is expressed numerically in terms of the "equivalent amount of aluminum" (in millimeters). A soft x-ray beam can be significantly reduced by a small amount of aluminum and, therefore, has a low HVL. Similarly, a hard beam will require a large amount of aluminum to reduce the radiation to one-half and therefore has a high HVL. Ideally, what is needed for a good image is a beam with a minimum HVL to ensure patient safety but one that contains photons at many different higher energy levels so that some photons will penetrate the tissue while other photons will be absorbed. A polyenergetic beam will produce the best image contrast.

Guidelines for the minimum values for HVL for each selected kVp are set by the federal government. These guidelines are established to ensure patient safety and all x-ray units must follow these standards. A list of the half value layer requirements can be found in the Appendix. A typical HVL for radiography is 3.0 mm of Al measured at 80 kVp. The service engineer must use the half value layer measurement to determine the minimum amount of filtration that must be added or removed from the beam to meet these guidelines.

FACTORS THAT INFLUENCE IMAGE QUALITY

Figure 22 shows the typical x-ray imaging chain for a radiographic room. Each of the highlighted items (and their geometrical relationship to one another) produces a significant effect on the final image. After the image is formed on the image receptor, the last factor affecting image quality is the viewing condition.

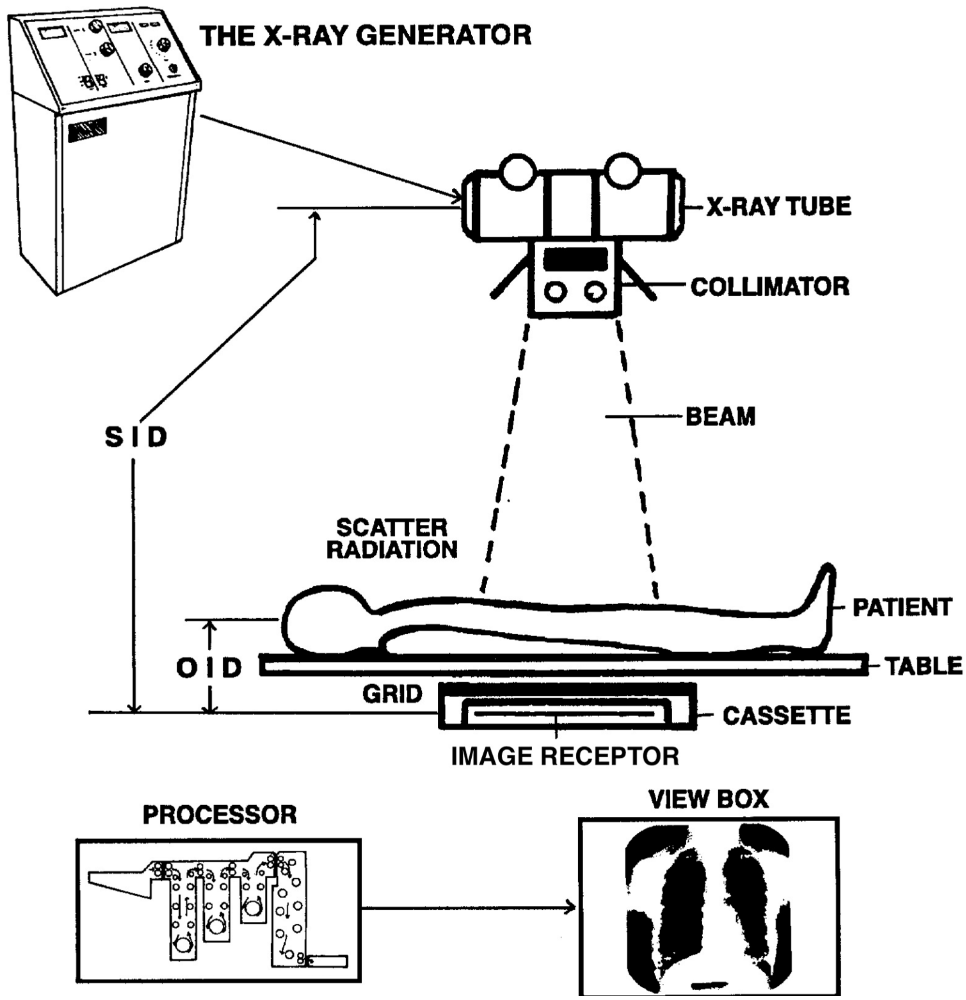

Figure 22. Factors that influence image quality. Each of these components has a significant effect on the quality if the final image.

The X-ray Generator

Technique Selection

Technique selection refers to the technique factors of kVp, mA, and time that are selectable at the x-ray control. These factors greatly influence the quality and quantity of radiation delivered to the patient per exposure and, therefore, directly affect image quality.

The selection of kilovoltage has two effects on image quality: it directly affects the beam quality which will greatly influence image contrast, and it also affects the overall image density. As stated above, beam quality refers to the overall energy level of the radiation present at a given kVp. At very low kVp settings, the beam consists predominately of soft radiation which will be absorbed by the patient and, therefore, will not contribute to the x-ray image. At high kVp settings, the beam consists of high energy x-ray photons that have greater penetrating ability. This hard beam will effectively reduce the dose to the patient but at a cost: a loss in image contrast.

As a rule, increasing the kVp will reduce image contrast. The loss in contrast is a result of (1) more x-ray photons reaching the image receptor (because of the higher penetrating ability) thus darkening the image overall and (2) increased amount of scatter radiation caused by the high-energy photons. Scatter radiation, as stated above, only reduces image quality.

A radiograph taken at 80 kVp that produces a normal image density will have noticeably more contrast than one taken at 100 kVp for that same density, all other factors held constant. This effect on image contrast applies mainly to large changes in the kVp setting. The human eye cannot detect a change in contrast when small changes in the kVp settings are made. Specifically, when the exposure rate is held constant, a change in +/– 5 kVp is not discernible to the unaided eye.

Second, an increase in kVp will cause more photons to reach the image receptor, and thus produce a greater image density. The increase in the quantity of radiation is, however, not proportional with the increase in kVp. For example, doubling the kVp from 50 kVp to 100 kVp will not double the image density, all other factors held constant.

Finally, the quality of the x-ray beam is affected by the type of kVp waveform. As stated in Chapter III, the kVp waveform is drastically different for single-phase generators, three-phase, and high-frequency generators (see Figures 4–7). At 80 kVp, the x-ray beam will be much "harder" for three-phase than for single phase because of the reduced ripple factor and higher efficiency of three-phase power. Consequently, a single-phase generator will produce more image contrast than a three-phase or high-frequency generator at that same kVp and image density.

The technique selection of mA and time also affects image quality, but in a way not related to image contrast. When referring to image quality, mA and time, or their product (mA x seconds, or mAs), directly affects image density and image sharpness. If the kVp is held constant, increasing a mA setting or the time setting will proportionally increase the overall density of the image.

The mA and time factors also indirectly affect how sharp the image will be. Image sharpness can be affected by three types of motion: x-ray tube motion, image receptor motion, and patient motion. To achieve a sharp image, the x-ray tube, image receptor, and patient must remain motionless during the exposure.

Because of the high-quality x-ray tubes and image receptors that are being manufactured today, their effects on image sharpness are negligible. Of all factors, patient motion has the greatest effect on image blurring. When longer exposure times are used, patient motion is the greatest factor that will affect the sharpness of an image.

Unfortunately, it is often very difficult to keep a patient perfectly stationary during long exposures for several reasons. First, the patient must breathe at some point during the exposure. The mechanical process of breathing can cause a significant amount of patient motion which will produce a blurry image. Other involuntary patient motion includes: heart motion, swallowing, and motion related to the physical condition of the patient. Patient restraints (i.e., straps that hold the patient in place) are only effective to a small degree. By increasing the mA setting, a shorter exposure time can be used thereby reducing the effects caused by patient motion.

A disadvantage of using a higher mA setting relates to the corresponding increase in the focal spot size caused by a phenomenon termed blooming. Blooming is a condition that results from the larger space charge at surrounds the filament during a high mA exposure. The larger space charge causes an increase in the effective focal spot size. The effects of blooming are critical in studies where extremely sharp detail is required (i.e., angiography) and for this reason x-ray tubes with very small focal spot sizes are most often used.

The X-ray Tube

Four characteristics of x-ray tubes have a significant effect on image quality. These are the focal spot size, the amount of inherent filtration, the type of anode construction, and the heel effect produced by the anode. Each of these four factors must be considered when evaluating the images produced from an x-ray system.

The focal spot size (or focus) of the tube directly affects the amount of detail (or sharpness) that can be observed in the image. When discussing the focus, we are specifically referring to the effective focal spot size of the x-ray tube. As stated in Chapter III, the effective focal spot size is dependent on a size of the filaments and the target angle.

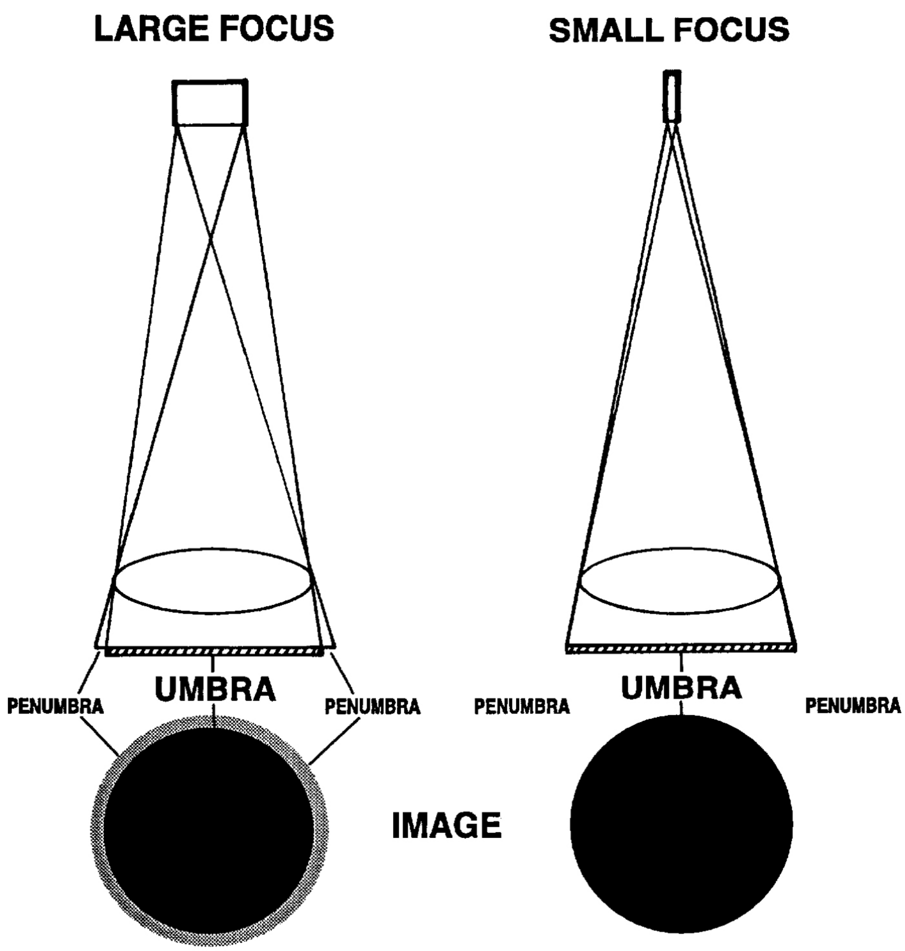

Figure 23. The effect of focal spot size. A smaller focus will produce less penumbra and therefore a sharper image.

The diagram in Figure 23 demonstrates the influence of focal spot size on image sharpness. The "shadow" created from an object exposed by a point source has two components: the umbra, which is the main shadow created by the object; and the penumbra, which is the lighter blurry area surrounding the umbra.

A smaller effective focal spot size produces less penumbra and therefore greater sharpness. However, because of the reduced exposure rating capabilities, it is not practical to always use small focus on every exam. For this reason, dual-focus tubes are widely used in general radiography. With a dual focus x-ray tube, small focus is used solely for studies requiring fine detailed images (or in most pediatric studies) and large focus is used for most other studies.

The focus of the x-ray tube is precisely measured at the tube manufacturing facility before it is shipped to the end user. In the field, x-ray tube focus is most commonly measured by service engineers with a test resolution phantom called a lead test star at the time of installation (see Chapter VII). With today's high standards used in manufacturing x-ray tubes, the focal spot size of the tube should remain relatively constant for the expected life of the tube. The engineer can check the focal spot size when a loss of detail is noticed on the image.

The second characteristic of x-ray tubes that affects image quality is the inherent filtration of the tube. Inherent filtration refers to the amount of filtration that is present within the x-ray tube assembly alone. Because of their construction, all tubes have a minimum amount of inherent filtration. Specifically, this filtration is a result of the combination of the glass insert, the insulating oil, and the tube housing port, all of which are in the path of the x-ray beam. The amount of filtration created by these materials is measured and recorded in equivalent millimeters of aluminum at the factory. This numerical value can be found in the x-ray tube data sheet that is supplied with the tube.

Since that amount of filtration affects the quality of the x-ray beam and, thus, image contrast, it is important to know the amount of inherent filtration of the x-ray tube. The inherent filtration must be considered in the total measurement of filtration in the x-ray beam.

As a rule, the inherent filtration will increase as the x-ray tube ages. This is due to the accumulation of tungsten that is deposited on the inside of the glass insert, resulting from filament evaporation. The increase in filtration can be compensated for by removing the appropriate amount of filtration located in the collimator (see below). When the inherent filtration of an x-ray tube becomes excessive, the tube must be replaced. Usually the tube will fail in another manner before the filtration reaches this point.

The third characteristic of x-ray tubes that directly affects image quality is anode construction. The material used in the target will dictate the type of radiation that will be produced. Tungsten is most commonly used in x-ray tubes for general radiography because it produces predominately higher energy x-ray photons. Molybdenum is used in mammography because it creates much lower energy radiation which is necessary for imaging soft tissue. Today most manufacturers of x-ray tubes utilize a combination of several different materials to achieve the desired beam quality.

A final characteristic of x-ray tubes that affects image quality involves the heel effect caused by the anode. As stated in Chapter I, x-rays disperse from the target in all directions. X-rays that travel in the direction of the anode are partially absorbed as they pass through the thickness of the target. This absorption will cause a gradual reduction in the amount of radiation in the beam when measuring from the center of the beam towards the anode end of the x-ray tube. The gradual reduction in radiation will result in a gradual change in density that is clearly visible on a radiograph. Also, the heel effect increases with smaller target angles.

To compensate for the heel effect, the service engineer will orient the x-ray tube with the anode in the direction of the thinner anatomy of the patient, usually at the head end of the table. In this orientation, the heel effect is negligible for most common studies and therefore will not degrade image quality.

The Collimator

The collimator contributes to image quality in several important ways. The primary function of the collimator is to reduce the size of the radiation field so that only the desired anatomy will be exposed. This action will result not only in a significant reduction in the total dose that the patient receives but will also significantly reduce the amount of scatter radiation created by the interaction of x-rays with the patient. As mentioned, scatter radiation is one of the greatest contributors to poor image quality.

In addition, the use of collimators effectively decreases the overall image density and will also increase image contrast. The collimator also removes off-target radiation, termed stem radiation. Stem radiation occurs when the electrons from the filament hit the target in areas other than the focal track. This produces off-focused radiation that will severely affect image sharpness. The upper set of blades and the "fingers" in the collimator assembly are used to remove stem radiation.

Another advantage of using a collimator is that it functions effectively to reduce the backscatter radiation originating from behind the image plane. Backscatter radiation is usually caused when the x-ray beam interacts with the radiographic table. If the shutters of the collimator are adjusted to the area of anatomy to be imaged, less radiation will be available to interact with the surrounding patient structures and the table, thus greatly reducing the amount of backscatter radiation.

Finally, an important function of the collimator regarding image quality is that it provides x-ray beam filtration. All collimators should provide a means to allow for the placement of the additional filters needed to achieve the correct beam quality as specified by federal guidelines. The collimator may be equipped with selectable aluminum filters, or there will be a slot provided into which various amounts of aluminum sheets can be placed. In addition, the x-ray beam must also pass directly through the mirror, found in all collimators, which also provides a small amount of filtration. The mirror is used to project the field lamp onto the imaging plane and is positioned directly in the path of the x-ray beam.

The appropriate amount of filtration that is needed is determined by performing the HVL measurements, and then the correct thickness of aluminum is added inside the collimator assembly. The reason the filtration is added at this point in the beam pathway is that any defects in the aluminum will effectively be "blurred out" and will not be visible on the final image. Consequently, all filters should be placed as close to the tube as possible.

SID and OID

When positioning a patient for a radiograph, there are two spatial variables that have a great effect on image quality: the source to image distance, or SID, and the object to image distance, or OID. The ser-

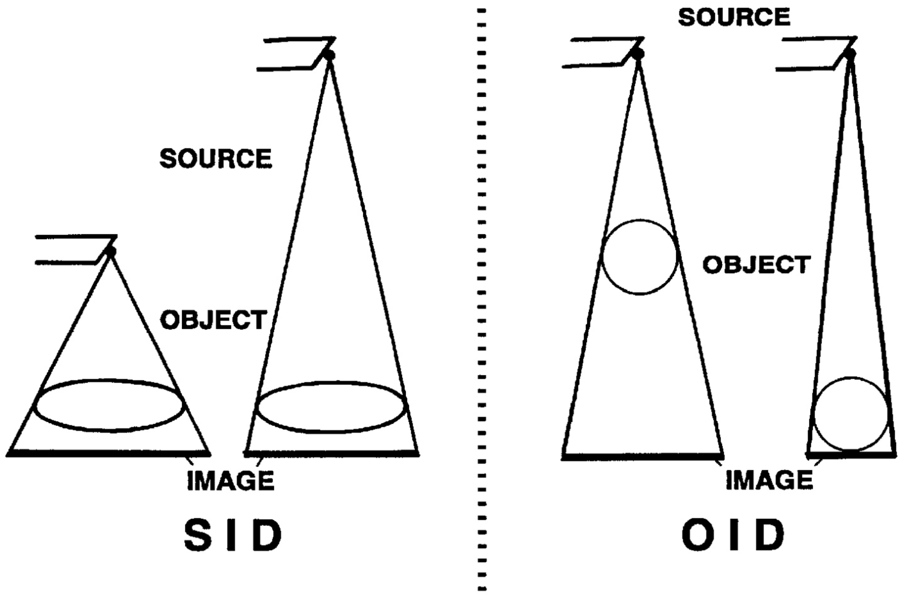

Figure 24. The effects of SID and OID. (Left): Increasing the SID will improve image sharpness and reduce image magnification. (Right): Decreasing the OID will improve image sharpness and reduce image magnification.

vice engineer must understand the effects caused by these geometric variables.

The SID greatly affects image sharpness. SID refers to the distance from the focal spot of the x-ray tube to the image plane. The diagram in Figure 24 shows the effects of varying the SID. As the SID increases, the focal spot appears to get smaller as viewed from the image plane. The effect of the smaller focal spot reduces the penumbra and improves image sharpness. Specifically, if choosing between the two most common SID's, 40 inches (100 cm) or 72 inches (180 cm), a 72-inch SID will produce a sharper image.

Changes in SID will also affect the image density. As the SID is increased, the x-rays must travel a greater distance to reach the image receptor plane. Since x-ray radiation must obey the Inverse Square Law, a significant reduction in radiation occurs at greater SIDs. This reduction must be compensated for by increasing the radiographic technique. Similarly, reducing the SID causes an increase in image density, all other factors held constant. A technique that produces a good image density at a 72″ SID will produce a much darker image at 40″ SID. Using the inverse square law for this example:

$I/i = d^2/D^2$

where: I = the new exposure rate

i = the original exposure rate

d = the original SID

D = the new SID

With D = 40 (new distance), d = 72 (original distance)

$I = (72^2/40^2) \text{ X } (i)$

$I = 3.24 \text{ X } (i)$

From the equation, it is seen that by reducing the SID to 40″, the exposure rate is exactly 3.24 times greater than the original exposure rate at 72″ SID.

Finally, reducing the SID also causes image distortion. Image distortion is defined as the misrepresentation of the true size and shape of an object. Size distortion is referred to as magnification. When the SID is decreased, image magnification increases. Shape distortion, the second type of image distortion, occurs because of improper alignment of the tube, patient, or image receptor.

The second spatial factor that affects image quality is the OID (object to image distance). OID refers to the distance between the patient and the image receptor plane. From the diagram (Figure 24), an increase in OID will result in a decrease in image sharpness. Moreover, an increase in OID causes significant image magnification which is undesirable for most studies. For the above reasons, positioning the patient as close as possible to the image receptor is the recommended practice.

For general radiography, two standard SID's are commonly used for most x-ray exams. A SID of 72″ is preferred when a sharp image with minimal magnification and distortion is desired. A chest exam, for example, is usually taken at 72″ SID. If the chest was exposed at a 40″ SID, the resulting enlarged image of the heart could possibly mask a lesion in the lung. The 40″ SID is, however, used for most other studies in general radiography. This distance was found to produce good imaging, especially for cranial and extremity radiography.

The Patient

In addition to the effects produced by radiographic equipment, another factor that directly affects image quality is the patient. We know from the preceding section that patient motion will cause a loss of detail because of image blurring and that by reducing the exposure time, the effects of patient motion will be reduced. It is the patient's internal structures, however, that will ultimately dictate how the final image will appear. Factors such as size, age, and pathology of a patient will greatly change the appearance of the final image. For this reason, the engineer must be familiar with patient morphology, standard imaging techniques, and some of the common disorders that radiography helps diagnose.

Tissue will absorb radiation in different amounts depending on the atomic number of the material and the density of the tissue. Bone, for example, absorbs significantly more radiation than does soft tissue. It is exactly this tissue specific variation of attenuation that creates an exit beam that produces an image consisting of a wide range of densities. The subject contrast varies greatly with patient type, age, physical condition, and patient pathology and must be considered when evaluating image quality. If the technique factors and geometrical setup are held constant, subject contrast will vary significantly between a large patient and a thin one. The larger patient will absorb much more radiation than the thin patient. In addition, there will also be more magnification of the internal structures of a larger patient because the organs are farther away from the receptor. Finally, a larger patient will produce more scatter radiation which, in turn, reduces image quality.

The age of the patient also affects the image. The muscle tissue of an elderly patient will produce an image that is drastically different from that of a young healthy patient. Bone density also changes with age and must be considered when evaluating an image. An osteoporotic patient will require a much lower exposure technique than a patient with normal bone tissue.

The physical condition of the patient will also affect image contrast and density and, therefore, should be considered when evaluating images. For example, a patient with lung disease will produce an image that will differ greatly in appearance, depending on the type of disease. An image produced from a person with asbestosis will differ greatly from that of a person with emphysema. Finally, the image quality will be greatly affected by a patient wearing a plaster cast or some type of prosthetic device.

The Radiographic Table

The radiographic table will also have a significant effect on the final image. Here, the tabletop, which supports the patient, is positioned directly between a patient and the image receptor–directly in the image pathway. Consequently, the tabletop must be comprised of materials that will not attenuate the x-ray beam and, thereby, cause a reduction in image quality. Technically, the tabletop should have high transmission and low absorption characteristics.

In addition, the tabletop must be homogeneous and free from defects that could produce image artifacts. In the past, tabletops were made mostly out of wood. Unfortunately, any defects in the wood, or the wood grain itself, will show up on the image. Most tabletops manufactured today are made from carbon fiber materials and, with rare exceptions, meet all the requirements stated above.

The Image Receptor Assembly

The image receptor, simply defined, is a detector that converts the invisible image to a visible one. Historically, the image receptor in a radiographic room was the film and film cassette. Today, the main image receptor (IR) most commonly used is the digital flat panel. For this discussion we will include the effects of the entire image receptor assembly since it plays a role in image quality.

The image receptor in a general radiographic room can be found in two places. The receptor located on a wall is used for erect studies. With the wall receptor, the patient is positioned so that he or she is standing directly in front of the image receptor, directly in the path of the x-ray beam. The other location of the image receptor is in the radiographic table, just beneath the tabletop.

The Grid Cabinet

For most radiographic applications, the exit beam must pass through an x-ray grid before it reaches the image receptor. X-ray grids, located in a grid cabinet, are generally used with all image receptors. The sole function of the grid is to reduce the amount of scatter radiation caused by the interaction of the x-ray beam with the patient. By reducing the amount of scatter radiation, image contrast is greatly improved.

For general radiography, both stationary and reciprocating grids have been used. A stationary grid remains motionless during the exposure and is usually located within the grid cabinet. Stationary grids are commonly used in general radiography rooms, are effective at reducing scatter radiation, and work well with most digital applications. Reciprocating grids were developed to further increase the amount of scatter reduction. Located in a Bucky, these grids will oscillate back and forth during the exposure. A reciprocating grid is more efficient at reducing scatter radiation than a stationary grid, but requires additional circuitry to create the grid movement. The added circuitry increases the overall cost of the receptor and has an increased potential for failure.

Regardless of the type of grid, they can be very costly mostly because of their special construction. Both stationary and reciprocating grids are made of thin lead strips separated by an interspace material. This inter-space material must have a low absorption quality to allow the x-ray photons to pass through unattenuated. Common interspace materials are fiber, aluminum, and air.

The lead strips are oriented parallel to each other in a linear grid, or, the strips can form a cross-hatch pattern as in a cross-hatched grid (Figure 25). Cross-hatched grids are more effective in reducing scatter than linear grids, but are extremely sensitive to x-ray tube positioning.

The most common type of grid used today is the linear grid because it allows for tube angulation for special radiographic views without causing grid cut-off (see below). Linear grids can be used effectively if the x-ray tube is angled along a path which is parallel to the lead strips. For this reason, the grid axis, indicated on the front (tube side) of the grid, must always be oriented in the direction of the tube angulation–in the head to foot direction of the patient.

With both types of grids, the lead strips are spaced to allow most of the primary beam to pass directly through to the IR, while impeding any scatter radiation traveling at angles to the receptor plane (Figure 26). Even so, some of the primary beam will also be impeded by the lead strips, reducing the overall amount of radiation hitting the image receptor. Consequently, the x-ray technique must be increased when using grids.

In fact, all grids are designed to operate at a specific range of kilovoltage, as indicated on the grid. If used out of this range, density variations will occur on the image. Also, the specified kilovoltage is direct-

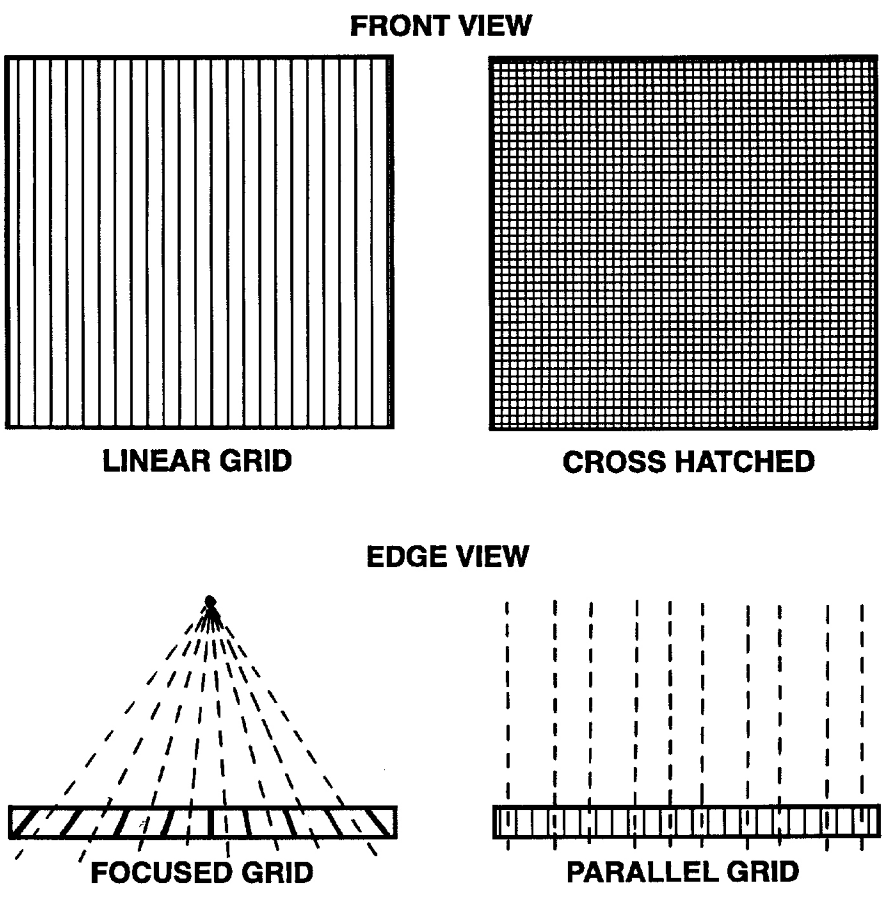

Figure 25. Types of x-ray grids.

ly dependent on the amount of lead in the grid. Consequently, x-ray grids with high grid ratio's and grid frequencies require higher KV setting.

The two major factors that determine how effective a grid is at reducing scatter radiation are the grid ratio and grid frequency. The grid ratio is the ratio of the height of the lead strips to the distance between each lead strip. A grid having lead strips that are 0.08 inches high, separated by 0.01 inches, has a grid ratio of 8 to 1. A higher grid ratio is more efficient at reducing scatter radiation.

With higher grid ratios, there is more lead for the radiation to pass through, and consequently, a higher exposure technique is required to achieve an adequate image density. Also, grids that have high grid

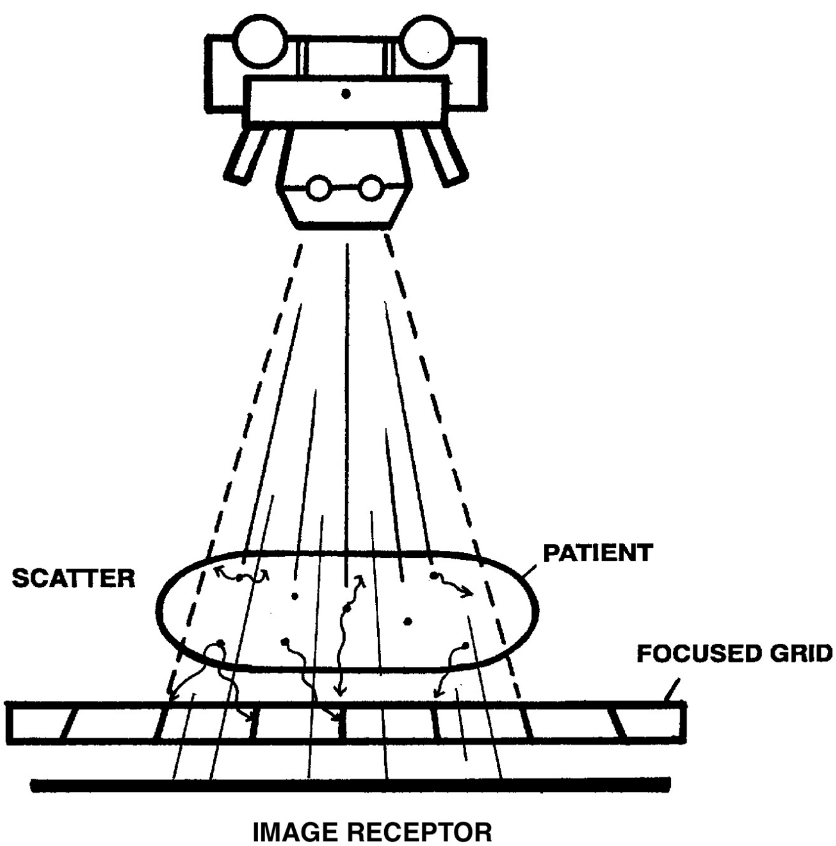

Figure 26. How the x-ray grid removes scatter radiation. Only radiation traveling in straight lines will reach the image receptor.

ratios are more sensitive to positioning than grids with lower ratios. If the tube is not perfectly aligned with the receptor, grid cutoff will result. It is for this reason that stationary grids with low grid ratios (e.g., 5 to 1) are used with mobile x-ray machines.

The grid frequency refers to the number of lead strips that are in the grid and is measured in grid lines per inch (or lines per cm). As the grid frequency is increased, the width of the lead strips will decrease to accommodate for the additional strips (while maintaining the same grid ratio). The thinner strips of lead found in a grid with a high grid frequency will not be visible on the image. A grid with thicker lead strips (or low grid frequency) will greatly reduce scatter radiation, but the image of the lead strips may appear on the image as grid lines.

When selecting a grid, a compromise must always be made between grid frequency and the amount of scatter reduction desired. Common grid frequencies used in radiographic rooms are in the range of 80 to 100 lines per inch. At these grid frequencies, the x-ray grid can effectively reduce scatter radiation without causing visible grid lines on the image.

X-ray grids can be either of focused or parallel construction, depending on how the lead stripes are oriented in respect to the axis of the x-ray beam. A focused grid has lead strips that are angled as they move away from the center of the x-ray beam. If lines were drawn through the angled strips, they would converge at a point above the film plane (Figure 26). The point where these lines converge is the focus point of the grid. Focused grids can be focused for a specific SID such as 40″, for example, or for an SID range such as 40″ to 72″ SID. The x-ray tube must be positioned at the point of focus or grid cutoff will result. This positioning is very critical with higher grid ratios.

With parallel grids, the lead strips are not angled but run parallel to the central ray of the x-ray tube. Parallel grids must be used with a large SID and small image size or grid cutoff will result. Parallel grids are often used in fluoroscopy studies.

Grid cutoff is caused when a significant portion of the primary x-ray beam is stopped by the lead strips. By impeding part of the primary beam, less radiation reaches the imaging plane and, consequently, a decrease in image density can be observed on all (or part) of the image. There are four types of grid cutoff, and each type produces an effect on the final image. The service engineer should understand the causes for each type of grid cutoff and the effects they produce on the image.

1. Off-center cutoff is a result of the x-ray beam not being centered to the grid. This type of cutoff produces a general decrease in density over the entire image.
2. Off-focus cutoff is caused by having the x-ray tube positioned out of the focal range of a focused grid. This type of cutoff produces lighter densities on the side borders of the image while the center remains unaffected.
3. Off-level cutoff when the grid is tilted in respect to the image plane and shows up as a general decrease in overall density of the image.
4. Reverse cutoff is caused by a grid that was positioned upside-down in the path. This type of cutoff results in a decrease in density around all borders of the image.

The Reciprocating Bucky

The Bucky is a special type of grid cabinet that moves the grid during the exposure. The grid used in a reciprocating Bucky can have a very low grid frequency (i.e., thicker lead strips) without causing grid lines. The reason for this is because the Bucky contains the additional circuitry that moves or "oscillates" the grid back and forth over the image receptor during the entire exposure. The grid "reciprocates" in the cross-Bucky (lateral) direction, at right angles to the lead strips. This cross motion effectively blurs the thicker lead stripes so that they will not be seen on the image. As stated earlier in this chapter, grids with a low grid frequency are more effective at reducing scatter.

A reciprocating Bucky requires a motor and drive assembly to cause the grid to oscillate. Also, the grid must move at the correct speed and must be synchronized with the x-ray generator or grid lines will result. The speed and synchronization of the Bucky motor are controlled by circuitry located within the x-ray generator cabinet.

The Image Receptor (IR) Assembly

As noted previously, the image receptor is the device in radiography that converts the radiation passing through the patient into a visible image that can be viewed for diagnoses. Located within the grid cabinet, it is the final component of the imaging chain involved in image formation. The image receptor has progressed from the film cassette (original) to the CR cassette (a hybrid), to the flat field detector (FFD), which is the best technology as of the writing of this third edition. All three receptors are discussed below because it is important to follow the technological developments that led to the digital flat panel.

The introduction of the film cassette marked a major advancement in general radiography mainly because light radiation was now exposing the film, rather than direct x-ray radiation. The film cassette (Figure 27) is a light-tight container that holds the unexposed x-ray film during the exposure. The cassette is inserted into a cassette tray or a cassette holder in a radiographic room, or it can be placed directly behind the patient in mobile applications. Film cassettes were manufactured for every standard film size used in general radiography.

The most significant component of the film cassette is the intensifying screens. The sole function of the intensifying screen is to convert the x-ray energy to light energy which will then expose the film. In fact, 98 percent of the energy that exposes the film is light energy. X-rays contribute only about 2 percent of the total exposure. By converting x-ray radiation to light energy, the light-sensitive film is exposed much more quickly than if exposed with direct x-ray radiation. The reduction in exposure time not only reduces the radiation to the patient but also extends the life of the x-ray tube.

The intensifying screen is a type of scintillator, converting high energy x-ray photons to light energy. The screens consist of a layer of phosphor crystals supported by a cardboard or plastic base. Since double-emulsion film (an emulsion layer on both sides) is used in general radiography, two intensifying screens are used inside the film cassette. The film is sandwiched between the upper and lower screens and is held firmly against each intensifying screen by springs that are also located within the cassette. Without the spring tension, there would be insufficient film/screen contact which would appear as blurring on the image. Good film/screen contact is needed to produce sharp images.

X-ray photons excite the phosphor crystals which emit light energy that exposes the film. The most common phosphor crystal used in the intensifying screens is calcium tungstate which emits light in the blue and ultraviolet region of the electromagnetic spectrum. Calcium

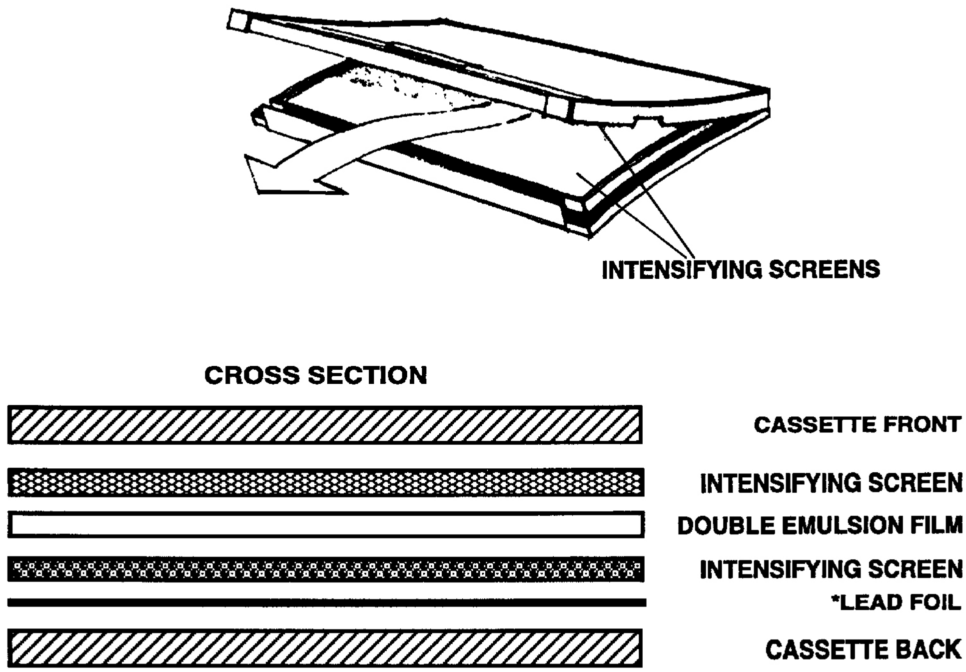

Figure 27. The film cassette. The lead foil is used to reduce backscatter radiation.

tungstate is used because there is very little lag (i.e., a quick response time) and it is very durable as a screen material. In later improvements to screens, rare earth phosphors were used because of their greater efficiency in converting radiation to light energy. Rare earth phosphors such as gadolinium and lanthanum emit light in the green region of the visible spectrum and must be appropriately matched with green sensitive film.

When discussing intensifying screens, the most important characteristic is screen sensitivity. The size of the phosphor crystals and the thickness of the phosphor layer determine the sensitivity of the intensifying screens. A screen that contains larger crystals or that has a thick layer of phosphor will give off significantly more light energy for a given amount of radiation than will screens with smaller crystals (or thin phosphor layer).

The increased light output of the larger crystals will result in much shorter exposure times. These screens are termed fast screens or high sensitivity screens. However, larger crystals will not resolve the fine detail of certain anatomical structures because of the increased amount of light output. Consequently, a fast screen has large crystals and produces less detail.

Where extreme detail is needed, a "slower," less sensitive screen is needed–one with smaller crystals and a thin phosphor layer. These screens, called detail screens, require a higher exposure rate to produce a density equal to that of the fast screens. Detail screens have small crystals which allows the radiologist to see intricate detail in the image. Detail screens are mostly used for extremity work and angiography.

X-ray Film

Since the inception of radiography, the image media where the final image is formed and permanently stored has been x-ray film. Double Emulsion x-ray film consisted of a base material made of plastic with an emulsion layer on both sides of the base. The emulsion contained silver bromide crystals that, when exposed to light, created the latent image on the film. The size of the silver bromide crystals determined the film speed, or film sensitivity. A fast film had larger crystals and less detail. Detail film had many more smaller crystals which produced a sharper image.

X-ray film could produce very good images but had its drawbacks. There were many external factors that caused inconsistencies in the appearance of the final image. X-ray film had to be matched with the correct intensifying screens to produce an optimum image. Using the incorrect film/screen combination would cause numerous image quality problems. Film had to be "fresh." It had to be stored at the proper temperature and humidity, and had to be used within an expiration date. Using film that was not properly stored (or out of date) would result in imaging problems. Film manufacturers had to utilize strict quality control methods to ensure that the film remained consistent with each lot of film produced.

Light leaks were a major issue. With use, film cassettes would get damaged, mostly from being dropped. Most of the damage resulted in air gaps causing light to partially expose the film. Film had to be handled in a darkroom. Darkrooms were specially built in medical facilities to store and process the film. These darkrooms regularly developed light leaks around the door jams and at the film processor's exit bin. Film was often accidently exposed, or partially "fogged" rendering it unusable.

As is evident, the x-ray technologist (and service engineer) faced many challenges with using film. In addition to focusing on x-ray equipment repair, the service engineer had to be knowledgeable of film and film processing. Radiology workers routinely monitored film quality by performing daily quality control procedures. With so many factors affecting image quality, it could be a challenge to obtain good images.

Film Processing

Besides the varieties in film and intensifying screens, a major factor that affected the image quality on film in the past was related to the development of the film, or film processing. Perfectly calibrated x-ray equipment will be of little use if the film processor was not working properly. In fact, without a properly functioning film processor, it was impossible to get a good radiograph. The film processor, in this sense, was the weak link of the imaging chain and the cause of many imaging problems. A brief look at film processing will help the reader to understand the challenges posed to radiography over the years.

During film processing, the film travels through a series of rollers to the developer tank, fixer tank, the water tank, and dryer, respectively (see Figure 28). The developer forms the image on the film by reducing the neutral silver deposits on the film to black metallic silver. When the film leaves the developer tank, the complete image will be visible on the film. The remaining stages of film processing will just make this image permanent. For this reason, the developing stage is the most important stage of film processing. Any problems encountered at this point will remain unchangeable.

The developer had to be active (fresh) and carefully maintained at a specified temperature or image quality would be affected. In fact, the temperature of the developer was the most important component in film processing that affected image quality. A variation of a few degrees in either direction would cause significant changes in film contrast. In addition, the film must remain in the develop tank for a specific length of time, called the immersion time, or improper development will occur. Finally, the developer must be replaced (i.e., replenished) at a constant rate, termed replenishment rate, to maintain the correct amount of reducing agent.

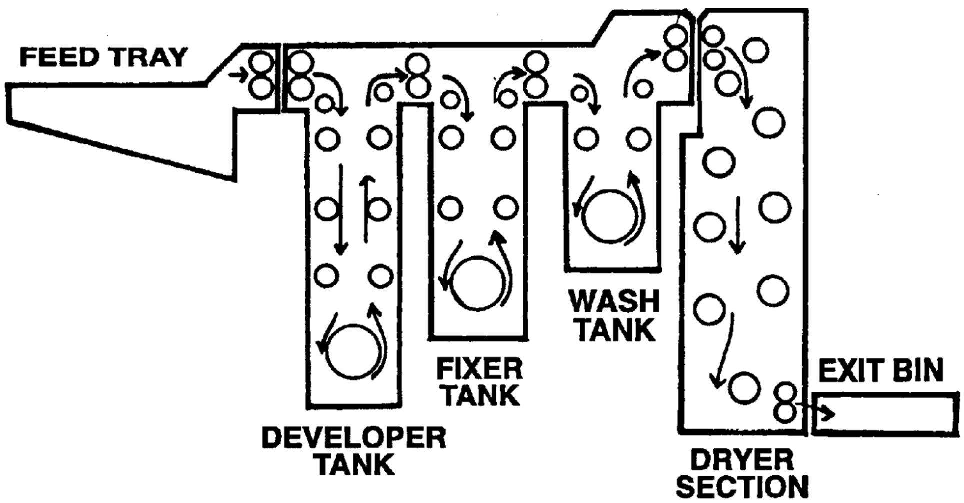

Figure 28. The automatic film processor.

Once the film was properly developed, it had to be "fixed." When the film travels to the fixer tank, several things occur. The fixer, usually made of ammonium thiosulfate, chemically stops the action of the developer and permanently fixes the image on the film. It does so by removing all the unaltered silver bromide crystals that were not exposed to light and, in effect, clears the film. If these unaltered crystals were left on the film, they would react with ambient light and cause a severe loss of image quality over time. The fixer must always remain fresh or it will not completely inhibit the developer. The fixer also contains hardeners that protect the film from scratches that may occur from routine handling.

When the film has finished traveling through the fixer tank, it is then rinsed thoroughly in the wash tank. All the unused chemicals are now removed from the film so that no other reactions will occur that could affect image stability. In addition, the film is washed to eliminate film artifacts, such as spotting. Water filters are usually inserted in the water supply line of the film processor to eliminate film artifacts caused by rust or salts in the water.

The dryer functions to completely dry the film after it has been rinsed. If the films are not completely dry when exiting the film processor, they will stick together in the holding tray at the output side of the processor.

Because of the inherent problems with film processing, it had to be monitored with a quality control program. It was a requirement that darkroom quality control (QC) be performed and recorded weekly. A good QC program ensures optimum image quality by monitoring the consistency of the film processing. The procedure requires that a test film be exposed with a "step wedge" of increasing densities by a device called a sensitometer. The exposed film is then "read" with a densitometer which displays the logarithmic value called film density. Next, a speed index, contrast index, and baseline reading are recorded on a graph so that the processor conditions are constantly monitored. Processor QC was time consuming but necessary to insure good x-ray images would be produced.

To sum it up, film technology was the dominant means of recording x-ray images until very recently. Film could produce high-quality images, but with so many variables, it was a challenge to produce consistent images. Looking back from a digital perspective, one is struck by the amount of time that had to be invested with film to ensure good image quality. Thankfully, today we have digital receptors that allow for consistent images throughout a variety of environmental conditions.

DIGITAL RECEPTORS

With digital technology, many of the variables associated with film that once affected image quality in the past have now been eliminated. With the advent of CR technology, and then, DR technology, image acquisition has become much simplified, image quality is more consistent, and image storage more efficient.

CR technology, a major advancement at the time, acted as a bridge between film technology and digital imaging. CR cassettes were a direct replacement to film cassettes, so no further modifications to the grid cabinet were needed. The cassette tray and grid cabinet could accept both film cassettes and CR cassettes. But rather than exposing film and then processing it in a film processor, the CR imaging plate was exposed like film, and then scanned using laser technology. The scanned image is digitized and further processed with imaging software.

CR technology truly had a major impact on radiology. CR scanners were compact in design and could fit easily into the x-ray control area. A darkroom was no longer needed. The digital images could be transmitted to a local server in the facility and made available for viewing at any work station. CR technology altered the landscape of radiology in a very positive way. As of this writing, CR units are still being used regularly.

But from a technical standpoint, the point of view any service engineer would take, the CR units were problematic due to their design. The CR unit employed rollers (like film processors), motor drives, belts, gears, electronic sensors, and microswitches. The many moving parts required routine service since mechanical assemblies, in general, are prone to failure. Gears and belts had to be replaced periodically to ensure optimum operation with minimum failures. Photomultiplier tubes, which are costly, degraded with age. After a scan is completed, the image plate must be erased using high-intensity lamps. Often, the lamps worked inconsistently and would not fully erase the image, thus leaving a ghost image that would appear on the next exam. In fact, the erase lamps had to be tested regularly in CR units to ensure that they were fully functional. Also, the image cassettes would fail over time, just as with film cassettes, developing light leaks, or causing jams inside the CR readers. CR technology represented a major step in the direction towards digital imaging yet, unfortunately, still retained a mechanical design.

With the advent of the flat panel detectors (FPD), the field of radiography skyrocketed into the future. With no internal moving parts, these panels could perform reliably for many years, providing consistently high quality images under a variety of environmental conditions. Flat panels require little maintenance. Certainly, image quality will gradually degrade as the internal electronic components age, but a simple panel calibration can correct any defects and return the panel to optimum performance. Even if the DR panel is dropped, which unfortunately happens–especially when dealing with uncooperative patients–any pixel defects can be removed with the software.

Once an image is captured by the flat panel, the image is digitized and sent to a computer dedicated to processing and viewing the image. The computer is equipped with specialized imaging software used to enhance and to modify the image to the radiologist's specifications. At the computer, the image can be resized, rotated, magnified, measured, and adjusted (window and level) for optimum viewing.

Furthermore, digital imaging is more forgiving in response to variations with exposure techniques. If the exposure technique was slightly off–overexposed or underexposed–the image can be adjusted and reprocessed to achieve a diagnostic image, thus avoiding a "retake." After the image is saved, it can be stored locally on the hard drive, or sent to a PACS system where it can be viewed by other radiologists at the same or another facility.

Viewing the Image

With film technology, a major component affecting how good an image can appear is the image viewer. When the completely processed x-ray film emerges from the film processor, it is ready for viewing. X-ray film must be brightly backlit to see all the varying densities that make up an image. The radiologist will view or "read" the film on a view box (or illuminator). An illuminator is an internally lighted box with an opaque screen on the front side. Fluorescent lights located within the view box provide the back lighting for the screen. When the film is placed on the opaque screen it will be illuminated by the fluorescent lights.

The main purpose of the view box is to provide even (ambient) lighting, at a specific intensity and color, across the entire viewing area. A view box that provides uneven lighting or low illumination will directly affect the radiologist perception of the image. This is especially true for mammography where proper illumination becomes extremely crucial. The guidelines for view box luminance, specified in average luminance, is 40 foot-lamberts or 1400 cd/m squared.

The room lighting must also be controllable in the viewing area so that the overhead lights can be dimmed to an acceptable level or shut off completely. In addition, any sources of stray lighting should be eliminated since it could affect the appearance of the image. The room should be dark enough so that the radiologist's eyes will become dark adapted. Under these conditions the human eye can better discern minor differences in light intensity on the film.

The same principles apply to viewing digital images. With DR and CR, the images are viewed on a high-resolution monitor in a designated reading room at the hospital or medical imaging facility. There is also a viewing monitor located at the workstation, usually on a computer at the x-ray control in a radiographic room. A laptop or tablet is used for mobile x-ray. These monitors are used by the technologist to check the image and apply enhancement processing if needed. The stored image is sent to a remote server where it can be accessed by the radiologist.

IMAGE QUALITY: A REVIEW

Historically, obtaining a good radiograph was an art that took years to acquire. Every device in the imaging chain affected how the final image would appear and each device had to be working optimally. There was also the challenge of matching film and film processing to achieve the best quality image for that system. The service engineer regularly had to fine-tune the entire x-ray system to maintain optimum image quality. Fortunately, with digital technology, those days are gone.

Looking back at Figure 22, which highlights the factors that influence image quality, we can now discuss how digital technology has greatly aided x-ray imaging. To begin with, most x-ray generators manufactured today are digitally controlled to output a high-frequency x-ray square wave that is accurate, consistent, and ripple free. These x-ray generators employ feedback control that precisely regulates the kV and mA outputs. And regardless of the equipment manufacturer, the output waveforms produced from high-frequency generators are similar. This commonality found with most x-ray generators of today eliminates a major variable in x-ray imaging regarding beam quality and dose.

Additionally, x-ray tube manufacturers produce high-quality radiographic tubes that have similar output ratings and filtration values– there is simply much more consistency in the industry today. Collimators can add or reduce filtration so that the radiation beam reaching the patient from most x-ray units is of the same beam quality.

Digital image receptors, overall, are manufactured with similar technology. Each company that manufactures flat panels offers slightly different advantages to their designs: quicker response, or higher resolution, for example. But otherwise, these panels operate similarly, producing good images at the standard doses used for exams. Each flat panel requires a specific x-ray dose to produce an optimum image. This is termed Exposure Index (EI). When the appropriate amount of radiation strikes the panel–when the specified EI is achieved, a good image should result. Manufacturers use different terms for exposure index, S value or Q value, for example, which indicates a range of doses that will produce the best images.

Regardless of the terminology, flat panels can produce a good image within standard dose ranges. As a result, universal x-ray techniques have been established that are optimized to provide high-quality images, with minimal dose to the patient. Organizations, such as NEXT (Nationwide Evaluation of X-ray Trends), regularly evaluate specific x-ray exams, collecting data from across the United States. This data is used to set standard x-ray techniques for each type of examination. It has been established, for example, that the optimum technique that will achieve a good image (with minimal dose) for an adult (AP) chest examination is 109 kV @ 10 mR (.10 mGy). Rather than an art, radiography has become an exact science. And these standardized x-ray techniques will work with any digital receptor. Now, a facility with a high-frequency x-ray generator and a digital panel can use standard radiographic techniques that will always produce quality images.

Furthermore, the digital images created from CR or DR technology are viewed on high resolution (2-5 MP) computer monitors. These high-quality monitors have eliminated many of the inconsistencies associated with the viewing conditions of the past. A radiologist located anywhere in the world can review an image under the same optimum viewing conditions. This was not possible to achieve in the past. We are seeing the best that the field of radiology can produce–at least for now.

Chapter VI

SAFETY IN X-RAY SERVICING

There are potential hazards that the engineer should be aware of when servicing of radiographic equipment. On the job, the service engineer will encounter mechanical hazards, electrical hazards, and x-ray radiation hazards. Because most radiographic equipment is installed in a medical environment where patients are routinely examined, there also exists a potential risk from the presence of biohazards. With an acute awareness of these potential hazards, the service engineer can make intelligent choices that will greatly reduce his or her risks while servicing equipment.

MECHANICAL HAZARDS

Many of the mechanical devices in a radiographic room can be potentially hazardous if not handled properly. The most obvious problem relates to the physical size and weight of x-ray equipment. As stated in the introduction, most x-ray components are large and very heavy. The x-ray tube, alone, can way over 40 pounds. The high-voltage transformer can weigh several hundred pounds, or more. Because of the excessive weight of these individual components, proper precaution must be exercised when moving or lifting equipment. In fact, many of the duties in x-ray servicing should only be performed with the aid of a second engineer.

The tubestand is designed to hold the x-ray tube in a range of positions. The main safety concern with a tubestand relates to the counterbalancing mechanism. As stated above, an x-ray tube can weigh 40 pounds. To provide smooth travel in the vertical direction, the tube

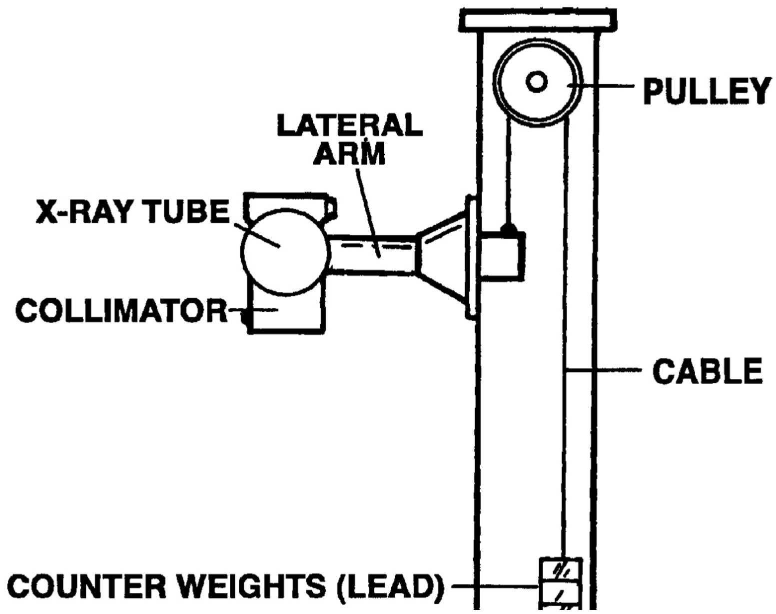

Figure 29. The tubestand counterbalancing system.

must be counterbalanced with a system of counterweights, pulleys, and cables (Figure 29). The counterweight system must be inspected on a regular basis to ensure its safe operation. Also, the counterweight assembly must be secured (locked in place) before any major service is performed on a tubestand.

The overhead tubecrane performs the same functions as a tubestand, but uses a different system for counterbalancing. Instead of using counterweights, tubecranes have a counterpoise system that employs spring tension for counterbalancing (Figure 30). A counterpoise provides smooth vertical motion allowing the operator to make tube height adjustments with ease.

When installing a new x-ray tube, or when major service is required on overhead tubecranes, a safety locking mechanism must be engaged. The lock secures the tube column in position, removing the dangerous spring tension force. Again, the cables and spring tensioner should be inspected on a regular basis and extreme caution should be used when working on this device.

The x-ray table performs two important functions: it houses the image receptor, and it facilitates positioning of the patient during an x-ray examination. Since most radiographic tables must support patient

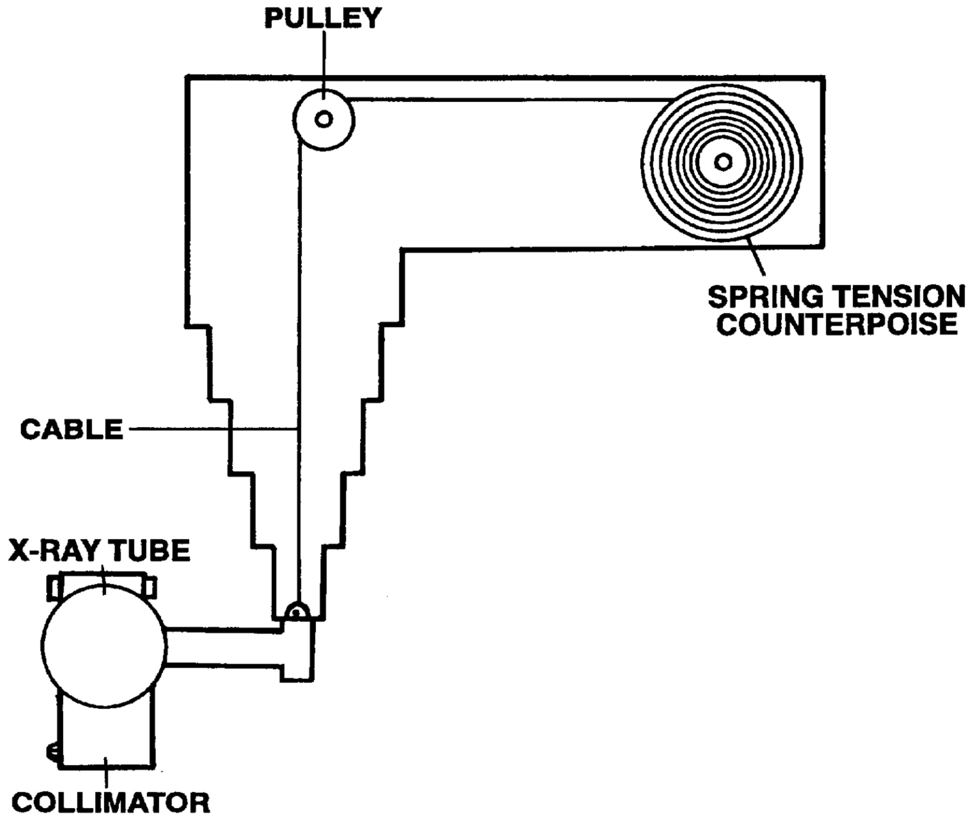

Figure 30. The tubecrane counterpoise.

weights of 300 pounds or more, they must be made of solid construction. Consequently, these tables are usually very heavy, often requiring special "table jacks" for lifting and moving the tables during the installation. Usually though, once the table has been mounted in place, the service engineer will rarely have to move it. The engineer may have to remove the tabletop on occasion. In this instance two engineers are required for lifting.

Another safety hazard involved with x-ray tables relates to the vertical drive system (if provided). The vertical drive system consists of a drive motor mechanically connected to a worm gear or chain drive system that raises and lowers the table. The motor is activated by a footswitch (or handswitch) and will drive the table up or down until it reaches a limit switch. The limit switch will then disconnect power to the motor.

As a rule, power should be turned off when servicing this type of x-ray table, especially when the service engineer is working beneath the table. If the engineer must have the table power "on" when servicing the table, the footswitch (or handswitch) for the vertical drive should be disconnected, ideally. This may involve removing the wires from the switch or from the terminal block in the table base. Although it takes a little extra time to perform, disabling the drive switch is easily done and well worth the effort. It is not uncommon to hear of situations where the service person was working inside a table and then accidentally leaned on the vertical drive switch and the table began to drive down on the engineer. By disconnecting the drive switches, such accidents can easily be avoided.

A wall receptor or erect Bucky is a device in the x-ray room that allows the technician to take exposures of patients while they are standing erect. The wallstand supports a Bucky (or grid cabinet) which holds the image receptor in place and allows the use of a grid and/or AEC detector. The vertical column is bolted to the floor and the Bucky moves vertically along the column to accommodate the heights of all patients. With manually operated wallstands, a counterweight assembly is used. Some wallstands are mechanically integrated to the tubestand and are driven vertically by a motor drive system.

The same precautions must be used when servicing the wall unit because of the counterweight or motor drive system. As a rule, two engineers are required when moving the tubestand.

ELECTRICAL HAZARDS

Potential electrical hazards exist when servicing x-ray equipment. Most of the devices found in a radiographic room operate with either AC or DC power–often both. The engineer should be familiar with the power distribution of the x-ray room prior to beginning service. He or she should be aware of circuits that are "live" and how to remove power from them. Most service documentation supplied by the manufacturer includes a power distribution diagram.

Also, special care must be taken when working in the high voltage circuits because of floating potentials and residual capacitances that are present in the circuits. With high voltage circuits the engineer must follow specific steps to ensure that the equipment is fully discharged prior to servicing. Countless tales exist of servicemen being "zapped" by high voltage because of careless practices. A mistake in this area can be lethal.

The electrical hazards in x-ray servicing are present in both the primary and secondary circuits of the x-ray generator, as well as in the auxiliary equipment in the room. The primary circuit begins at the incoming voltage supplied by the power company and includes all components that are connected up to the primary winding of the high voltage transformer. Safety precautions must be observed when working in this area because of the potentially lethal voltages, which can be as high as 480 VAC for three-phase systems.

An input voltage, as specified in the service literature, is fed to the main breaker panel in the x-ray room, and is termed the "primary feed." The breaker panel is often located near the x-ray control and should be identified and labeled. Sometimes there are several breaker panels in the room: one panel providing dedicated power to x-ray generator power and other breaker panels supplying power for auxiliary equipment such as the collimator or table.

Before removing any equipment covers, the engineer should remove all power by switching off the breakers. Turning the power switch off at the generator control will not completely remove the power from inside the generator cabinet. The reason for shutting off the main breaker is to eliminate the chance of an accidental short circuit when the engineer removes or replaces the metal equipment covers. The compact designs of today's equipment sometimes result in very little space between the metal covers and live connections. Once the equipment covers are removed, a quick check of the power feed connections at the generator with a voltmeter will confirm that no power is present. With many high-frequency generators, the capacitors in the power section may retain a charge for several minutes after the equipment is powered down. The service engineer should ensure that the capacitors are fully discharged before beginning service. These voltage checks should become a routine safety practice when servicing equipment.

With the equipment covers removed and power off, the engineer can perform a physical inspection and analysis of the components in the primary circuit. Once the generator is inspected and the service engineer is familiar with the layout of the primary components, the main breaker can be switched on for further troubleshooting. With the generator powered on, troubleshooting can safely be performed by following these important guidelines:

1. Always probe live circuits with one hand only, keeping the other hand away from the generator.
2. Never connect test equipment to a live circuit. Always turn power off first, then attach the leads of the test meter to the circuit. Many times, the "hot" test points (i.e., voltage present) are directly adjacent to zero reference or ground points.
3. Make sure the test leads are securely attached to the component under test.
4. Use insulated tools when probing live circuits.

The secondary circuit begins in the secondary winding of the high voltage transformer and includes the high voltage cables and the x-ray tube. High voltage is present at any point in this circuit. In addition to high voltage, a low voltage (high current) supply for the filament circuit is also present on the cathode of the secondary. The engineer should demonstrate extreme caution in these areas.

When working in the secondary circuit, attention should be paid to several areas. One hazard involves the residual capacitance associated with the high-tension cables. These cables are made of heavy wire conductors separated by an insulating material (or dielectric). This is, in fact, the definition of a capacitor. Therefore, when current is traveling through the high-tension cables, they become charged.[6]

During the exposure, the cables become charged to a relatively high potential during the exposure and may not completely discharged when the exposure is terminated. This means that the high-tension cables cannot be safely handled unless they are fully discharged first. The service engineer can discharge the cables by grabbing the insulated portion of the cable and touching the pins of the federal connector to a ground point on the x-ray tube housing or the high voltage transformer. Once discharged, the cables can be safely inspected or connected to test equipment.

If using invasive test equipment such as a high voltage divider, the service engineer should make connections as specified in the instruc-

6. This capacitance influences the high voltage waveform.

tion manual of the test equipment being used. The engineer should also check to see that the unused wells are filled with oil when making parallel connections

The high voltage transformer unit should not have any power applied to it when it is being serviced. All internal components should be discharged before the service engineer attempts to work inside the transformer unit. A grounding rod is provided with some transformers to accomplish discharging.

All other devices in a radiographic room, such as the table, collimator, or tubestand, are usually powered by standard line voltage (110 VAC in the U.S.). The service engineer should also use caution when working on these devices. In addition, many low voltage circuits exist, logic supplies, for example. Although caution should be used when troubleshooting these circuits, mistakes often result in damage to the component rather than the service engineer.

RADIATION HAZARDS

Before servicing radiation producing equipment, the engineer should have a good understanding of the nature of x-rays. Most people know that exposure to radiation is hazardous and should be avoided, but by knowing the specific properties of radiation and how x-rays interact with matter the service engineer can make intelligent choices on a service call that will minimize his or her exposure.

Working around radiation can become routine after a few years in the x-ray servicing business and there is a tendency for service professionals to become lax in their safety practices. It is emphatic that the service engineer know when the x-ray unit is energized and producing radiation. This point cannot be stressed enough, and must always be first and foremost on the service engineer's mind. Furthermore, he or she should always adhere to the basic rules when working around radiation: standing behind protective barriers when taking exposures, wearing protective lead shielding, and keeping proper distance from the radiation source.

It is a fact that a career in the x-ray servicing profession requires some exposure to x-ray radiation. To properly diagnose and repair x-ray equipment, the engineer will take many exposures on a service call. In fact, it is not uncommon for the service engineer to take 30 or more exposures during an x-ray calibration. Consequently, if the proper safety precautions are not taken, the service engineer could be exposed to significant amounts of radiation. Conversely, with the proper education on radiation safety, the service professional can spend an entire career in this field with minimal exposure to radiation.

Since x-rays are invisible to the human eye and can only be detected with special test equipment, the service engineer should understand the nature of radiation and how x-rays react with matter. A brief overview of the properties of radiation follows.

The Nature of the Primary Beam

Earlier, we discussed the principles of x-ray production. Here, a more detailed description is provided. When the accelerated electrons collide with the target in an x-ray tube, two types of radiation are emitted: Brems (or braking) radiation and characteristic radiation. Brems radiation is produced by the sudden deceleration (braking) of the electrons as they impact with the target. Brems radiation contains x-rays of many different energy levels and, in fact, makes up most of the primary beam at the techniques used in medical diagnostic x-ray. The primary beam is, thus, referred to as polyenergetic.

The second type of x-ray radiation, characteristic radiation, occurs when the accelerated electron hits a target atom and causes an inner orbital electron of that atom to be ejected. This creates a hole in the inner shell of the electron which must then be filled to make the atom stable again. When this hole is filled, radiation of a distinct (characteristic) frequency for that atom is released. Characteristic radiation makes up only a small percentage (10%) of the primary beam for diagnostic radiation, and is only present above 70 kVp. Both Brems radiation and Characteristic radiation pass through the patient to form the image.

How X-rays Interact with Matter

X-ray radiation is a form of electromagnetic radiation. Like visible light, x-ray particles also travel at the speed of light and in straight lines. However, because of their higher energy level, x-rays differ from all other forms of electromagnetic radiation in that they react with the matter that they encounter.

When x-rays penetrate the body, two things can occur. The x-rays may simply pass directly through unaffected or, they may be absorbed into the body and interact with the atoms within the tissue. The ability for x-rays to pass directly through tissue is referred to as the penetrating ability. The penetrating ability is a function of the energy level of the x-rays and is directly related to the amount of kV applied to the x-ray tube (see Chapter V). The x-rays that are absorbed into tissue will interact with the surrounding tissue and will exit at some lower energy. This attenuated, lower energy exit beam is, in fact, what forms the latent x-ray image.

However, those x-rays that are absorbed in the body will interact with tissue in a way not related to the image formation process that can be hazardous to the patient. X-rays can ionize of matter. Ionization is the process of removing or adding an orbital electron of an atom, and thus creating an unstable ion. Ionization of living matter is known to cause chemical and biological damage (i.e., it destroys tissue). Another result of the interaction of x-rays within the body is that the high-energy x-rays can liberate heat when passing through matter which can also damage living tissue. Both the ionization and heating of tissue can potentially occur during an x-ray examination. However, limiting the exposure time will minimize or eliminate the effects completely.

When considering radiation safety, a third phenomenon of x-ray interaction must be discussed. When x-rays interact with matter, two additional forms of radiation are produced, scatter radiation and secondary radiation. Scatter radiation and secondary radiation can harm the patient, and are a major source of radiation exposure to the radiologist, the x-ray technologist, and the service engineer. These two forms of radiation also greatly affect image quality.

Scatter and secondary radiation are produced by distinct interactions with matter. The interactions that are of the greatest importance in diagnostic radiology are the Photoelectric interactions and Compton interactions. In Photoelectric interactions, the x-ray photon is absorbed into an atom and that atom then gives off an orbital electron which creates an ion as described above. The orbital electron that was ejected becomes a high-energy photoelectron and when the hole is filled in the atom, characteristic radiation is emitted.

Both the photoelectron and the characteristic radiation are forms of secondary radiation. Because each material (i.e., bone, soft tissue, etc.) will give off its own characteristic radiation, the photoelectric effect contributes to image contrast and, therefore, plays an important role in forming the final image.

In Compton interactions, the x-ray photon collides with an outer shell electron in tissue and is deflected off in different direction at a lower energy state. These deflected, lower energy photoelectrons are referred to as scatter radiation. Scatter radiation, because of its lower energy and random nature, does not contribute to the image but, in fact, reduces image quality. In addition, scatter radiation is a main source of exposure to healthcare professionals working in radiology. During an x-ray examination, the primary beam is focused tightly on the patient, collimated to a small area of the desired anatomy to be imaged. Since the primary beam is directed at the patient, it is not the main source of radiation exposure to those performing the examination. It is the softer (low energy) radiation deflecting from the patient (or the table or receptor) that can expose the staff indirectly to radiation. From a serving perspective, the point to emphasize is that with scatter radiation the x-rays are no longer just traveling in one direction (i.e., towards the image receptor) but now travel in many directions including towards the service engineer while he or she is testing or calibrating equipment. The engineer should know that scatter radiation exposes the patient to more radiation than necessary, can be hazardous to the equipment operator, and decreases image quality. An important goal in radiography is to reduce the amount of scatter radiation as much as possible.

Radiation Measurements

Since x-rays cannot be detected by the human senses, indirect methods of detection and measurement must be employed. Most test instruments used for radiation measurements take advantage of the ionizing effects of radiation. Some of the effects of ionization are:

1. It causes chemical changes as with photographic film.
2. It causes certain materials to glow, such as phosphor.
3. It excites gases.
4. It "energizes" solid state detectors.

One method of detecting and measuring radiation is by using an ionization chamber. The air within the ionization chamber, or probe, becomes ionized in proportion to the amount of radiation it receives and can be electrically measured. Many radiation physicists use this type of device to measure the output of x-ray generators and to calculate entrance doses delivered to patients. X-ray service engineers will also use the ion chamber detector for certain calibration procedures. Newer methods of detection employ solid state detectors within the probes which conduct current proportionally to the amount of radiation.

Radiation Measurement Units

For many years the standard unit of measurement for radiation output of x-ray equipment was termed the Roentgen (R), named for the discoverer of x-rays. The Roentgen is defined as the amount of radiation needed to ionize one cubic centimeter of air to one electrostatic unit. As a rule, x-ray service engineers will measure radiation output using "R" units (typically mR) when performing compliance testing and, therefore, should be familiar this unit of measurement.

When measuring radiation that is absorbed into living tissue, or entrance dose, other measurement units must be used. Although entrance doses can be measured in "R" units, it must be emphasized that the Roentgen is based on ionization free in air, and does not take into consideration the effects of scatter radiation. For measurements that include scatter radiation, there are two other units commonly used: the RAD and the Gray or Gy.

The RAD is a measurement of radiation absorbed dose (in tissue). One RAD equals the absorption of 100 ergs of energy per gram of irradiated matter. The Gray is the international unit of absorbed dose and is equal to 1 joule of radiation energy absorbed per kilogram of tissue. The relationship between the RAD and the Gy is: 1 RAD = .01 Gy.

As stated, the RAD and Gray take into consideration the backscatter factor of tissue. Since scatter adds to the total amount of radiation absorbed in tissue, it is important to know what unit of measurement is being used when dealing with entrance doses. Since the Roentgen does not account for this. A measurement of entrance dose given in "R" units must be multiplied by a conversion factor of 1.21 to get the RAD equivalent.

Not all types of radiation, however, produce the same effect in tissue. Alpha particles, for example, produce much more injury to tissue than the same amount of x-ray radiation used in a diagnostic x-ray exam. To account for this difference, two other units of measurement were developed that take into consideration the Relative Biological Effectiveness (RBE) in tissue due to various types of radiation.

For x-ray radiation, the two units of measurement of absorbed dose are the REM and the international unit, the Sievert (Sv). One REM is equal to one RAD multiplied by a quality factor. For diagnostic x-ray radiation, the quality factor is, conveniently, equal to unity (or one), and therefore, 1 RAD = 1 REM (or 1 Sv = 1 Gy).

It is known that certain tissues are more susceptible to radiation damage than others. For example, the hands can receive much more radiation than the eyes or gonads, without increasing the risk factor for cancer. Most guidelines for radiation exposure, however, are stated for whole body accumulated dose. The legal limit for radiation workers is 5 REMS per year (whole body). If an x-ray service engineer's yearly accumulated dose is below this value, he or she can safely work in this field without increasing his or her risk factor for cancer.

Radiation Monitoring

Historically, the primary method commonly used to monitor the amount of radiation received by individuals who work around radiation was by wearing a film badge. The film badge was worn by the service engineer, radiologist, and x-ray technician on a specified area of the body for a given period (usually one month). The badge is then sent to a testing laboratory where it is analyzed for the amount of radiation that was recorded on the film. The results are documented in a monthly report and sent back to the individual. Today, since x-ray film is no longer used, digital detectors are used, instead, as personal radiation monitors. This type of personal radiation monitor can be can be read instantly on a computer and the results stored on a permanent record that can be printed out when needed.

Radiation Safety

With a thorough understanding of the nature of x-ray radiation and how it interacts with matter, the engineer can take the proper safety precautions that will reduce his or her exposure. Anyone working around radiation should follow the radiation safety guidelines referred to by the acronym, ALARA (As Low As Reasonably Achievable). The three things that the engineer can do to reduce (or eliminate) the amount of exposure to radiation he or she receives are:

1. Use the proper *shielding* when taking exposures.
2. Maintain a maximum *distance* as possible from the x-ray tube.
3. Reduce the amount of *time* that x-rays are being emitted.

The service engineer should always take x-ray exposures from behind the lead barrier in the control booth during calibrations and testing. If the engineer must be in the x-ray room while exposures are being taken, he or she must wear the proper lead shielding. This includes a lead apron, thyroid shields, and lead gloves if placing objects in the path of the primary beam.

If possible, the collimator shutters should be closed when performing x-ray testing to reduce the exposure to the service engineer. The service engineer should never make exposures with the collimator completely removed from the x-ray tube. The collimator provides significant shielding from radiation that exits the tube in many directions. If exposures must be made without a collimator in place, a lead blocker must be placed on the port of the tube.

The second factor that can greatly affect the amount of radiation exposure that the engineer will receive while servicing radiographic equipment is distance from the x-ray source. The service engineer should always observe the inverse square law, which states that the intensity of radiation at a given distance from a point source is inversely proportional to the square of the distance. This means that when the engineer stands a certain distance from the x-ray tube and is receiving a known dose, increasing the distance from the tube by a factor of "two" will effectively reduce the radiation dose he or she is receiving to one-fourth.

Taking advantage of this property of radiation is one of the most important steps that an engineer can take to significantly reduce his or her exposure. The service engineer can safely work in this field if he or she is conscious of his or her surroundings, and the proximity to the x-ray source.

The third factor that will reduce the service engineer's exposure to radiation is time. Simply put, if the engineer reduces the amount of time he or she is taking exposures, personal exposure will correspondingly be reduced. The engineer should avoid taking unnecessary exposures when troubleshooting x-ray problems. This obvious point is often overlooked by the service engineer who becomes "engrossed" in a complicated x-ray problem and is not conscious of the amount of exposures that he or she is taking.

Furthermore, troubleshooting should be performed using the shortest possible exposure times that will allow the engineer to make a diagnosis (this practice also keeps x-ray tubes from overheating). Since exposure to radiation has an accumulative effect on tissue, each individual exposure that the engineer receives must be added to the total amount received throughout his or her lifetime. For example, a person who receives a single exposure of 5 RADS suffers the same risks as a person who receives 5 exposures of 1 RAD each.

The service engineer should always wear a personal monitoring device when servicing equipment and should review the monthly exposure reports. Finally, the engineer should never place any part of the body in the path of the primary beam. He or she should use appropriate phantoms to check image quality. A practice used many years ago in x-ray service was to place one's hand (or other body part) directly in the radiation field to check image quality. This practice, however, is very dangerous and not, at all, necessary.

BIOHAZARDS

In addition to the mechanical, electrical, and radiation hazards associated with servicing x-ray equipment, other potential biohazards exist within the medical environment. All healthcare workers, including x-ray service engineers, are at risk of being exposed to any number contaminants found in medical facilities. Medical equipment can be contaminated by blood and urine, or any secretions or excretions from a patient. There are risks from infectious materials and bloodborne pathogens such has HIV(AIDS) and HBV (Hepatitis B virus) and staph bacteria (MRSA). The engineer must have an awareness of the potential risk of infection from these biological hazards when servicing equipment.

The service engineer will, on occasion, be required to service equipment that has been contaminated with body fluids such as vomit, urine, feces, or blood. Oftentimes the fluid itself will cause the failure of the equipment.[7] The point is that the danger of infection to the service engineer is very real and ever-present.

Universal precautions should be taken to prevent contact with potentially infectious materials. The equipment must be cleaned thoroughly, preferably by a facility staff member, before the engineer begins servicing. The cleaning fluid must consist of a strong disinfectant solution, usually available on the site.

In addition, the engineer must wear personal protective equipment when working with contaminated equipment. Rubber gloves should be worn when cleaning up spills. Goggles or face shields should be worn when larger spills are involved because of the possibility of splashing. Gowns and shoe covers should also be worn when working on heavily contaminated equipment. The service engineer should not hesitate to ask for the protective equipment because of the serious nature of infection from bloodborne pathogens.

Finally, the engineer should perform hand hygiene after working on equipment. When work is completed, or if taking a break, the engineer should wash his or her hands completely with soap and water. And although an obvious point the engineer should never take food into the x-ray room.

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7. Bodily fluids are very conductive and will "short out" components with which they come in contact.

Chapter VII

THE INSTALLATION OF RADIOGRAPHIC EQUIPMENT

The installation of radiographic equipment requires knowledge and expertise in a wide range of disciplines. The service engineer (here termed, "the installer") should have some knowledge of building construction since he or she will be securing x-ray systems to walls, floors, and ceilings. The installer should understand how power is distributed within the facility and know how to safely work with electrical wiring and circuits. X-ray equipment is generally large and very heavy. Knowledge of the proper techniques for moving, lifting, aligning, and mounting equipment is required. New equipment must be programmed, configured for the specific application, and calibrated. The installer should possess good computer skills and electronic calibration skills. Successful equipment installation can be challenging so it is important that the installer be knowledgeable in all of these areas of expertise. For students, installations are the perfect setting to see how a complete x-ray system is interfaced and calibrated. Working with an experienced senior engineer, the student can learn the skills required for an installation.

When the installation has been completed, the room must look aesthetically pleasing. A good room layout design is needed to accomplish this goal. Great care must be taken when designing a room layout to ensure that the radiographic equipment will fit in nicely with the rest of the fixtures in the room and not be physically restricted in any way. A radiographic room that is attractively laid out will present an image that reflects positively on the equipment installer (and his or her organization).

While the engineer is performing the installation, all wiring changes and special modifications should be documented in the service manual. It is extremely frustrating for a service engineer to attempt servicing x-ray equipment that has been modified from the original manufacturer's design when there is no appropriate documentation of the modification at the site. Equipment with circuits that have been modified (or disabled) should be noted in the service literature and the actual modification should be clearly spelled out on the schematic. Also, all pertinent blueprints and schematics that show the exact power distribution and cable runs should be stored with the equipment manuals. Without this information, future troubleshooting can be difficult.

Once the installation has been completed, the room should be carefully tested by a senior service person so that any items that may have been overlooked or that do not meet specification can be corrected at this time. When the room is ready for operation, the engineer may be asked to demonstrate the safe and proper operation of the equipment (user inservicing), although this task is usually performed by a clinical application specialist. After the room has been in operation for a month or so, the engineer should revisit the site to check on any problems that might have been encountered during the "break-in" period.

The installation of any radiographic room, whether a new installation or a reinstallation of used equipment, can be divided into several stages. These are:

1. Site Planning
2. Room Preparation
3. Prestaging Equipment
4. Equipment Delivery
5. Equipment Alignment and Mounting
6. Calibration and Adjustment
7. Final testing
8. Installation/PM Checklist
9. User Inservicing
10. Follow-up

This chapter will review a general procedure for the installation of a radiographic room covering all the stages listed above. These guidelines can apply to most brands of x-ray equipment. After reading this chapter, the service engineer should have a good understanding of what is to be accomplished during an installation. However, when installing x-ray equipment, the specific installation instructions of the equipment manufacturer should be followed. The manufacturer's manuals are written specifically for their equipment and will include adjustments and calibration procedures that are required for their systems.

SITE PLANNING

The radiographic room should be designed so that the equipment will perform to the customer's expectations as specified in the sales agreement. To accomplish this goal, site planning meetings are arranged between the customer and the equipment dealer. A service engineer must be present at these meetings to provide any technical information that is needed.

Several factors influence the location of the x-ray devices within the room. The equipment layout is mainly dependent on the equipment footprint and the x-ray tube to image receptor alignment. Often, the cables that interconnect between the various x-ray devices in the room are restricted in length and will limit the number of layout possibilities. Other considerations in room layout are: patient accessibility (i.e., with stretchers or wheelchairs), service accessibility, and convenience for radiologists and technicians when performing studies. These points can be addressed with a good room layout drawing or blueprint. The blueprint is a scaled drawing of the actual room and is used by the contractor during the room preparation phase. Usually, the hospital staff, along with representatives from the equipment dealer, work together to produce the best possible room layout.

If the equipment is being installed in an existing x-ray room, the blueprint for that room will aid in the decision as to where the new equipment will be located. By using the existing framework and conduit, the cost of the new installation is greatly reduced. Also, the lead shielding should have been installed in the walls and doors for the original room so no additional costs are required. The usual practice is to follow a similar layout of the existing room. This can be easily accomplished with only minor compromises.

If the equipment is being installed at a new site, more preparation is needed and greater cost will be involved. On the positive side, there is more flexibility in the layout design with new construction. The service engineer can dictate exactly where the electrical wiring conduit should run, where junction boxes should be mounted, and the number and size of wires that should be pulled through the conduit. Also, if any walls, ceilings, or floors need to be reinforced to support the new equipment, it can easily be done with new construction.

The specifications for all building materials (i.e., supporting framework, lead shielding, electrical wire) and any applicable building code requirements are usually listed on the blueprint. This information is also available from various sources including the equipment manufacturer, the building inspector, the director of operations at the medical facility, as well as from the contractor who is performing the work. However, information on the radiographic equipment specifications, specifically the equipment size and weight, power requirements, and environmental operating conditions, is available directly from the equipment manufacturer and is usually included with the service literature.

In the past, when film was used, the darkroom was included in the layout design. With digital technology, darkrooms are no longer needed which results in sizable savings for the facility. No additional plumbing or ventilation is needed–no more loud noise and caustic odor.

Other important details must be considered when designing the layout of an x-ray room. Care should be taken to ensure that the equipment is installed with future servicing in mind. Each piece of equipment in the room should be installed so that it will be easily accessible for servicing. The equipment cables for each device in the room should be long enough to allow for easy movement. Many times equipment, which can only be serviced through the rear panel, will be positioned directly against a wall. In this case, the service engineer must be able to move the unit away from the wall to gain access to the rear panel.

Also, the control console, if possible, should be in close proximity to the x-ray power cabinet (for high-frequency units) or the high voltage transformer (for single and three-phase units). This is done so that one service engineer alone can conveniently perform troubleshooting and calibration procedures on the system. The service engineer must be able to connect test equipment to the generator section of the x-ray unit and view measurements while taking exposures at the x-ray control. The experienced engineer will be able to decide the best layout of the equipment so that all parts are accessible for repair and that the proper room lighting is available to aid in servicing.

Once the plans have been drawn and accepted by all the parties involved, a preliminary time schedule for the installation is made. This time schedule shows the projected timeline for room preparation, equipment delivery, and room completion. Certain circumstances, such as construction problems, or damaged or missing equipment, will occasionally arise causing the preliminary schedule to be revised. However, it is in the best interest of all parties concerned to stick to the preliminary schedule if possible.

ROOM PREPARATION

With a detailed blueprint, the contractor can proceed with the room preparation. It is at this time that the ceiling and floor supports are installed, the lead shielding is installed, all electrical conduits are laid out, and the power is brought to the main breaker panel in the room. Also, all lighting and ventilation systems will be installed. Generally, the room is painted, the flooring is laid during the room preparation phase. The x-ray service engineer should visit the site during room preparation to ensure that everything is going as planned and to advise if changes or problems have been encountered. Also, all inspections should be made at this time by the local building inspectors and state radiation physicists.

PRESTAGING EQUIPMENT

While the room preparation phase is taking place, the x-ray service engineer can uncrate and inventory the new equipment, which, ideally, is stored at the equipment dealer's warehouse. Many of the x-ray devices can be configured for their intended operation while at the warehouse and then tested ahead of time. The process of setting up and configuring equipment is called Prestaging. By prestaging equipment, the engineer can be sure that the correct equipment has been shipped to the site, and that it is operational and will work as intended.

Prestaging will absolutely reduce the actual time of the installation. Many important tasks can be completed during prestaging phase that will reduce the actual installation time at the site. These include:

1. Uncrating and equipment inspection
2. Inventory check
3. Equipment configuration
4. Power-up testing

Uncrating Equipment

When equipment is shipped from the manufacturer, it is packaged in large, reinforced crates to ensure safe shipping. This special packaging is no longer necessary once the equipment is safely in the dealer's warehouse. By uncrating the equipment, the service engineer can then carefully inspect each item for damage. Furthermore, the equipment can also be transported more easily to the site without the bulky crates. Usually, there is not enough space available at the installation site for these crates anyway.

Before the equipment is uncrated, a visual inspection of the crate itself should be performed. A damaged crate indicates mishandling during shipping and possible damage to equipment. Any damaged crates should have been documented at the time they were delivered for insurance purposes

Once the equipment is out of the crate, the engineer should look for any signs of physical damage due to faulty manufacturing or shipping. These signs include dents or scratches on the equipment surfaces and any damaged or missing hardware. In addition, the condition of the paint on each device should be checked for uniformity and the correct color must be verified. All moving parts for each device should be checked for smooth operation and the bearings and bearing tracts also inspected. The hardware and brackets for each piece of equipment should be inspected and tightened, if necessary.

Inventory

After each device has been inspected for physical damage, an inventory check should be performed. Each item should be checked against the shipping list, and then compared to the original purchase order. The inventory check should include not only equipment but also accessory items such as cables and user manuals. The engineer should check that all cable lengths are correct, as some cables are manufactured specifically for the job and are not a stock item. If a new cable must be ordered, for instance, it could delay the installation several weeks. Finally, during the inventory check, all the serial numbers should be recorded and documented on the installation report and on the equipment registration forms.

Equipment Configuration

If every piece of equipment is accounted for and in good physical condition, the service engineer can begin to configure the equipment for its specific use. Configuration is a process of programming the equipment both mechanically and electronically for its intended use at the facility. Mechanical configuration involves installing the correct hardware so the equipment will operate properly as specified in the room layout. Specifically, wall receptors and collimators will be configured for left-hand or right-hand operation, the proper x-ray tube mounting hardware must be installed for the type of tube support used, a Bucky or grid cabinet must be installed in the x-ray table, and the rails for the overhead tubecrane (if applicable) must be cut to length.

Electronic configuration includes any special wiring that must be installed on each device, the setting of dip switches on circuit boards, and software programming. Any special cables that are needed should also be cut to length and terminated during this phase.

X-ray Generator Configuration

The specific functions that are electronically programmed in the x-ray generator include the type of incoming power, the number and type of x-ray tubes being used, the number of image receptors, the presence of the AEC option, the type of rotor controller being used, and any special radiographic applications that will be installed. Configuration is usually accomplished by installing jumpers and setting dip switches in the most basic designs, or by software programming. With software programming, the service engineer will enter a "service mode" at the x-ray console and enter all the specific parameters into memory.

Line Matching

The engineer must configure the x-ray generator for the exact line voltage that is provided by the facility. Line matching must be performed on all generators before power can be applied. If the generator is not configured for the exact incoming line voltage, the proper calibration can never be achieved; even worse, the equipment could be permanently damaged.

Configuring the generator to match the incoming line is accomplished by pre-wiring the line autotransformer inside the x-ray generator. Most x-ray generators are equipped with an autotransformer that can accommodate a wide range of input voltages. The engineer sets the proper tap on the autotransformer to achieve the optimum operating voltage of the generator. If the required tap for a given input voltage is not available and no other source of power is available in the building, then a separate, external line matching transformer must be used.

X-ray Tube Protection Programming

X-ray tube protection programming is a vital step in the generator configuration process. The purpose of this programming is to ensure that the tube will operate safely within its designed limits during the x-ray examination. Once the generator is correctly programmed, the operator will be prevented from selecting an exposure technique that exceeds the tube rating specification for that x-ray tube.

For the "tube protect" circuitry to function properly, the exact characteristics of the x-ray tube must be known. The engineer can refer to the x-ray tube rating charts for information about the tube being used. These charts are supplied by the manufacturer of the x-ray tube and are usually shipped with the x-ray tube. The tube rating charts contain all the specifications of the x-ray tube insert in graphic form, including anode heating and cooling charts, filament emission charts, and exposure rating charts. Also, information about focal spot size and maximum continuous filament current is provided.

Additional information regarding the tube housing is also provided with the tube rating charts. This includes the type and power requirements of the stator, the maximum allowable voltage for the housing type, and the thermal ratings for the tube housing.

The engineer should be comfortable with using the tube rating charts and must know how to interpret the data they contain. If the charts are not interpreted properly, the x-ray tube may not operate at its full capacity, or even worse, may operate over its maximum rated capacity. Fortunately, today most equipment arrives equipped with software to accommodate the most common x-ray tubes use in general radiography. In this case the engineer just selects the tube type in the software and all the programming is completed automatically. For reference, however, a sample tube rating chart is provided in Appendix B along with guidelines on how to interpret it properly.

Power-up Testing

Power-up testing should be performed as a final check to verify equipment condition. Most of the time, testing is done to each piece of equipment separately, that is, not yet connected as a system. Before applying power to the unit, any wires, plugs, or connectors that may have become dislodged during shipping should be checked and reconnected. In addition, all circuit boards should be reseated into their edge connector since they also may have become dislodged during shipping. Some x-ray generators cannot be powered-up with an open secondary circuit (i.e., without an x-ray tube connected). In this case, the manufacturer's procedure for safe power-up should be followed.

When performing power-up testing on an x-ray generator, all the panel lamps and indicators should be checked for proper functioning, and all the switch functions should be tested. Microprocessor-controlled units usually have built-in, power-up diagnostic checks that are automatically performed when the unit is first turned on. These diagnostic programs will send an error code to the console if any problems are encountered during the "boot up" period. The error code will point directly to the area of the failure, thus saving much valuable time during the installation. In addition, many generator functions can be tested via the keypad at the console during this time.

Once powered-up, the unit should be left on for a few hours to allow the components to warm up and reach their normal operating temperature. Defective components will often fail during this period. If a failure occurs, the engineer can order replacement parts before the equipment is delivered to the site. If the generator passes the power-up testing and there is sufficient time, the installer can inspect and test the x-ray tube.

X-ray Tube Inspection

Before an x-ray tube can be installed into the system it should be physically inspected. Unfortunately, no one can be sure how the x-ray tube was handled during shipment. These tubes are heavy and could have been dropped, or left out in very cold weather–or extreme heat. So, the tube housing should be examined for dents or for any signs of oil leakage that could indicate a defective seal. The engineer should then check for the presence of air bubbles inside the housing. This is done by looking directly into the port of the tube while gently rocking it, first by lifting the cathode end and then lifting the anode end. If any air bubbles are observed, the tube is defective and must be sent back to the tube manufacturer for reloading. The engineer should closely inspect the anode surface by shining a flashlight directly into the port of the x-ray tube. The anode surface should appear smooth and uniform. Any obvious signs of defects such as cracks, pits, or warping should be documented and the tube should be returned for repair.

If the x-ray tube passes the physical inspection, then no further tests are needed at this time. The tube can be repackaged in the shipping box and stored until it is shipped to the site. The x-ray tube will be fully tested during the final stages of the installation.

With the completion of the generator and x-ray tube testing, all the other equipment that will be installed in the radiographic room, such as x-ray tables, tubestands, and receptors should be examined. Again, it is vital to know if any parts are defective before they are transported to the installation site. The wall receptor can be configured for left- or right-hand operation. All wiring and cable lengths should be verified to ensure that they will be long enough for the room where the equipment will be installed.

EQUIPMENT DELIVERY

When the room preparation has been completed and the prestaging has been performed, the equipment is ready to be delivered to the site. The smaller items should be placed back in the original packaging for safe transport. Larger components that have been removed from the heavy shipping crates should be wrapped with padding to prevent dents or scratches to surfaces.

The x-ray service engineer should be present at the site when the equipment arrives. This is important because the inventory will be verified again, and all items checked for damage. Also, the engineer can direct the movers, if they are not x-ray service engineers, in the specific placement of the individual devices. Heavy equipment such as the high voltage transformer should be set in their exact location as specified by the blueprint. If an overhead tubecrane is used, it should be installed directly into the ceiling tracks at this time with the help of the moving crew since the heavy lifting equipment (e.g., a highjack) is now at the site and there is more manpower present to help with the lifting. As always, the installer should follow the guidelines for installing the tubecrane onto the railing system.

The installer should adjust the bearings so that the tubecrane travels smoothly along the entire length of the rails. This is a very important step because the bearing adjustments are not always accessible when the tubecrane is positioned in the rails. Also, it is very difficult to take down the tubecrane after the rest of the equipment has been fully installed in the room.

If a tubestand is being installed, it should be taken into the room by the movers and temporarily mounted at its specified location. This is done so that the correct cable length can be run from the x-ray generator to the tubestand. Since several accurate measurements must be made before the tube support can be permanently fastened in place, the floor and ceiling tracks should only be fastened with the minimum amount of hardware to hold it safely in place. During the alignment procedure, the floor and ceiling track will be repositioned and then permanently fastened. Important to note is that the location of the tubestand will dictate where the table and wall receptor will be located (see below).

Next, the x-ray generator control cabinet and the high voltage transformer should be secured at the location specified in the blueprint. If a separate control console (or operator console) is used, it is usually located in the operator's booth and is mounted on a shelf, or on a pedestal stand if one was ordered with the system.

The x-ray table is usually positioned last because it takes up so much space in the x-ray room. In this case, the best approach is to mark an outline on the floor of the exact location of the table. By doing this, the installation can proceed more easily. Any cables that run to the table can be sized up and laid out using the outline on the floor.

When most of the equipment is positioned in the room, the service engineer can get a good feel as to the final appearance of the completed room. This is important because if some item was omitted or not correctly listed on the blueprint, a heating vent or radiator that was not listed, or a door opening outward versus inward, for example, the room may not operate as promised. If last-minute changes need to be made, the installer can make the appropriate changes to the actual room layout before each device is permanently fastened in place.

EQUIPMENT ALIGNMENT AND MOUNTING

With the equipment roughly in place, and the moving crew departed, the installers will precisely align the x-ray equipment. The main goal now is to get every device in the room aligned properly and then permanently mounted in place. Proper alignment is necessary to acquire good images. Essentially, the center of the x-ray beam (or central beam) must align to the center of each image receptor in the room. With a good equipment alignment, the technologist can move the x-ray tube through a range of SIDs and tube angles, yet remain centered on the image receptor. This phase can be the most challenging and is usually done with an experienced installer on site.

To accomplish the alignments, the x-ray tube and collimator must be mounted on the tube support since they are used to align each image receptor. Once the tube and collimator are mounted, the installer will run the cables and connect power to the x-ray system as quickly as possible so that the alignment procedure can begin. At a minimum, the collimator should be powered up so that the collimator lamp can be used to align the tubestand and wall receptor.

Mounting the X-ray Tube

There are two types of x-ray tube housings used in general radiography rooms. One type of housing has a raised mounting surface located at the port of the tube with four predrilled and tapped screw holes. The raised surface attaches directly to the tube support by threading the four head bolts through the mounting plate of the tube support directly into the four threaded screw holes provided on the x-ray tube housing.

The second type of x-ray tube housing is mounted to the tube support using trunnion rings. The trunnion rings of the tube support attach to the two raised (circular) ring surfaces on the tube housing. The trunnion rings allow for tube rotation for special radiographic views. With the trunnion mount, the tube is placed in the bottom half of the trunnion ring assembly and then the top trunnion ring is positioned on the top of the x-ray tube and then secured with four bolts.

Installing the Collimator

As stated in Chapter IV, the collimator limits the primary x-ray beam to just the area of interest and provides shielding for off-focus radiation. It is, therefore, the most important radiation safety device in the radiographic room. The installer should take great care to ensure that the collimator is installed correctly and performing properly. Because it is limiting the beam that exits the port of the x-ray tube, it is mounted as close to the tube as possible, either directly to the x-ray tube or to the tube mounting plate of the tube supporting device (Figure 31). Most collimators in general radiography use a swivel-type mounting bracket so that the collimator can be rotated.

The most important part of mounting the collimator is determining the number of spacers that must be placed between the collimator and the x-ray tube. The proper spacing is needed to provide the correct focal spot to collimator distance as specified by the manufacturer of the collimator. If the incorrect number of spacers is used, the light field dimensions will not correlate to the x-ray field dimensions. Light field to x-ray field congruence is a requirement of all collimators and will be verified during the collimator set-up procedure.

Also, if SID indication is provided on the collimator, those readings will not be accurate unless the correct number of spacers is used.

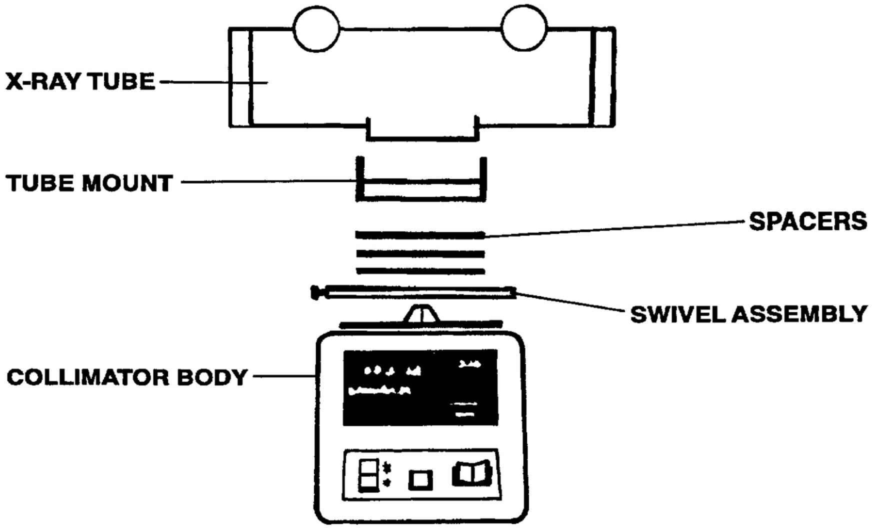

Figure 31. Collimator mounting. The correct number of spacers are required to achieve accurate SID indication.

The information packet provided with the x-ray tube contains a measurement of the location of the focal spot in respect to the port of the x-ray tube (where the collimator will attach). This dimension is used to determine the correct number of spacers required.

The spacers, made of steel, are provided by the manufacturer of the collimator and are inserted in between the collimator upper swivel bracket and the x-ray tube port. If the tube is mounted directly to the mounting plate on the tube-stand, the thickness of the plate must be considered when calculating the spacer dimension. Once the spacers and upper swivel bracket are in place, the collimator itself can be attached to the upper bracket.

Supplying Power to Each Unit in the System

With the tube and collimator mounted, the next step is to apply power to the collimator since we use the collimator light and cross-hairs to align all of the receptors in the room. At this point in the installation all cables can be run and terminated. Since each unit is in its approximate location, the amount of cable needed can easily be determined. Once the cables are terminated and power is applied to the tube and collimator, the installer can proceed with the alignment procedures.

Types of Equipment Cables

Three types of cables are commonly used in x-ray equipment: power cables, signal cables, and high voltage cables. Each electrically operated device in an x-ray room requires at least one power cable, but most devices need both power and signal cables.

The main power cable connects the x-ray generator to the incoming power via a circuit breaker panel located (ideally) within the x-ray room. Power cables are made of heavy-gauge wire (6 AWG, for example) surrounded by a thick insulating jacket. These power cables usually are not terminated (i.e., they have bare wire at each end) and are directly fastened to a terminal block. The cable used to connect primary power to the high voltage transformer is also made of this heavy-gauge wire.

The service engineer must make sure the wire is the correct gauge and type of wire so that the equipment will operate safely and at the manufacturer's specifications. An underrated power line will greatly reduce the output of the x-ray generator due to excessive line loading. The specifications for wire size and type are found in the service manual for the equipment.

Besides the main power line, each electronic device in the room will also need a power cable to operate. These power cables, however, are used to supply lower voltages, AC or DC, to power the individual devices in an x-ray room and are usually made of much smaller-gauge wire (e.g., 10-12 AWG wire).

Signal cables are used to interface specific x-ray devices in the room so that they can communicate with each other and thus perform as a system. These cables are usually made of much smaller-gauge wire (18 AWG or smaller) surrounded by a conductive cover or braid for shielding purposes, and enclosed in a flexible outer jacket. Signal cables are usually terminated with appropriate connectors at the factory and are plugged directly into each specific device during the installation. Care must be taken when pulling these cables through the conduit so that the connectors are not damaged.

The high voltage cables are a special type of power cable that connects the high voltage transformer to the x-ray tube. These cables are designed to carry extremely high voltages and are, therefore, heavily insulated. Besides being thicker than most cables, high voltage cables are terminated with a special plug called a federal connector (Figure

14). Because of the size of the federal connector, high voltage cables are the most difficult to pull through conduit.

Running Cables

All cables should be run inside of a special conduit (termed cable trough or raceway) which should have been installed during the room preparation phase. These cable “passageways” are located along walls, above ceilings, or under floors. The task of running cables is much easier if the raceway has removable covers. In this case, all the cables are simply placed in the trough and the covers are then fastened in place.

Nevertheless, running the cables through conduit in the ceilings and floors is difficult and usually requires two service persons. An electrician’s fish tape, or “wire fish,” is used to pull the cables through the conduit and cable grease, available at electrical supply stores, is used to help the cables slide more easily through the conduit. If the cables from the previous installation are still present inside of the conduit, they can be used to pull the new cables through. This is not always possible because the older cables are usually removed during the room preparation phase.

Procedures for Pulling Cables with a Wire Fish Tape

1. Insert the wire fish tape at the destination end of the cable run (where the device is located) and feed it to the point where the cables originate (the power source).
2. Attach the cables securely to the fish with electrical tape. Be sure that the cable is properly secured so it will not become detached while pulling. If the cable is terminated with connectors, these should be carefully taped so they are as streamlined as possible.
3. Apply cable grease at the point where the wire fish meets the cable. If other cables are in the conduit, apply grease to the entire cable to make pulling easier.
4. Gently pull (fish) the cable through with the fish tape while the second person pushes or “feeds” the cable from the other end.

This procedure should be followed for all the cables in the room. As a rule, power cables should be separated from signal cables in the raceway to eliminate future problems caused by line "noise." Usually dividers are present inside the raceway to shield the individual cables.

External Cable Layout

Cables that are run externally to the ceiling-mounted tubecrane, or to the floor to ceiling-mounted tubestand, must be laid out, or "hung," so that the tube support can move freely without stress applied to the cables themselves. If the cables are not hung properly, the tube could have limited motion in certain directions. More importantly, improperly suspended cables will receive undue stress as the device is moved through its range of positions. A cable that is constantly stressed or overflexed will prematurely break and will have to be replaced, which can be time consuming. The goal for the service engineer is to hang the cables so they move as little as possible.

The cables must also be aesthetically pleasing to the eye since they are in plain view to anyone in the room. An x-ray room with poorly hung cables leaves an overall bad impression of the room. If the cables run along a ceiling rail, they should be hung so that they don't stand out and move fluidly with the device to which they are attached. If the cable run is very long, a method of hanging the cables using coils or loops is often employed. If coils are used, attention should be paid to the size and number of coils, again for aesthetic reasons.

The process of hanging cables properly is an art that takes time to develop. It often takes several attempts with just one cable to find the best position for that cable. The service engineer should take as much time as needed to complete this task successfully. It is a process that should never be rushed.

Cable Termination

Once positioned and hung, the cables should be terminated and connected to the appropriate equipment. The service engineer "terminates" a cable by adding the appropriate connector (or terminal) to the ends of the wires. These connectors are most often fastened to the wires by using a crimp connection. As stated earlier, some cables are terminated at the factory and, therefore, are simply plugged into their designated connectors.

When connecting power cables, strict attention should be paid to polarity and grounding. In addition, a phase rotation meter (or oscilloscope) must be used to achieve the correct line phasing when installing three-phase generators. The collimator, tube support, and table power can be wired directly to terminals in the generator power unit so that the equipment in the room can be powered-up by just switching the main on/off switch at the generator control.

Every cable should be connected at this point in the installation. The high voltage cable ends should be coated with vapor proofing (see Chapter VIII) compound before they are connected to the x-ray tube. Each cable should be identified, labeled with an adhesive wire marker if not already done, and then checked to see that the wire numbers agree with the schematic. Many times the wire markers will be removed accidentally when the cables are pulled through the conduit. If this happens, the wire should be relabeled. Having the wires properly labeled will help engineers when troubleshooting on future service calls.

The installer should document any modifications on the equipment interconnect diagram showing any special interfacing that was performed. The service engineer who will service this system in the future will appreciate the extra step taken by the installer.

Counterbalancing

When the x-ray tube and collimator are mounted, and the cables are connected and properly hung, the tubestand or tubecrane can be counterbalanced. As stated in Chapter VI, the tube support must be counterbalanced so that the tube can be positioned in the vertical direction with minimal effort. The most common counterbalancing system consists of steel cables, pulleys, and special counterweights. This type of counterbalancing system is commonly used on tubestands and wallstands.

By adding counterweights supplied by the manufacturer, the tube can be balanced so that it will not drift up or down when the vertical locks are released. The tube should not drift at any point over the entire range of travel. Ideally, the tube should move up and down with very little effort and should come to rest immediately when released.

A different method of counterbalancing the x-ray tube is used in overhead tubecranes. Instead of being counterbalanced with weights, a spring mechanism or counterpoise is used. Since the spring mechanism is adjustable within a limited range, a compartment is provided within the tubecrane assembly so that the installer can add additional weights if the spring tension cannot be adjusted for the correct counterbalance tension.

X-ray Beam Alignment

Before permanently securing each device in the radiographic room, the engineer must first precisely align the x-ray beam to each of the image receptors. This is a primary goal of the installation. The installer should take care to precisely align the x-ray tube so that the x-ray beam remains centered on the image receptor throughout its entire range of motion–vertically and horizontally. Essentially, the tube/receptor axis dictates where each device will be fixed in the radiographic room. Once the tube/receptor alignment is achieved, each device in the room can then be permanently mounted in place.

To align the x-ray tube to the receptor, the installer must know the exact direction of the x-ray beam, or central ray. Because x-rays are invisible, the collimator light field is commonly used for this alignment procedure. Ideally, the installer should first verify that the light field of the collimator correctly matches the actual x-ray field. But since all new collimators are factory aligned, we can assume that the light field and x-ray field match exactly so the installer can skip this step. We will verify light field/x-ray field accuracy later during the calibration procedure.

This is an important phase in the installation because after this stage is completed, the major physical part of the installation is over, and the engineer can concentrate on calibrations and adjustments. Also, since a lot of dust and noise is created while the installer is drilling holes and mounting equipment, it is best to complete the physical mounting of the equipment as soon as possible. The staff at the facility will certainly appreciate the extra effort to complete this phase. After the equipment is permanently mounted and the room thoroughly cleaned, it will begin to look like a completed x-ray room.

Overhead Tubecrane/Wall Receptor Alignment

The overhead tubecrane travels on ceiling rails that run along the length of the x-ray room. These ceiling rails should have been installed by the contractor so that they run perfectly parallel with the length of the room, as specified on the blueprint. Since the tubecrane is mounted directly to these rails, it should also run parallel with the length of the room. A way to check the tubecrane alignment is to angulate the x-ray tube so that the x-ray beam is directed towards the wall where the receptor will be located and then to lock it in place. The installer should move the tube at a distance 40 inches to the wall, turn on the collimator light, and place a mark on the wall at the center of the collimator crosshair pattern that is projected onto the wall. While moving the tubecrane away from the wall, the service engineer should observe the light field in relation to the mark on the wall. The crosshairs should remain on the mark, tracking accurately for the length of the rails.

If the tube does not track perfectly in the left to right direction, then the ceiling supports were not installed correctly and the long axis of the equipment will be slightly different from the axis of the actual room. If the alignment is off by a small degree, the rotation of the tubecrane should be adjusted. If the tube does not track in the vertical direction, this indicates that the ceiling is sloped. This rarely occurs with new construction. Minor corrections can be made by shimming the ceiling rails. Sometimes it is impossible to achieve perfect tracking in the vertical direction for the entire length of the room. In this case, the engineer should then concentrate on aligning the tubecrane in the usable range for the wallstand (40″–72″ from wallstand). Once the tubecrane is perfectly aligned to the wall, the installer can permanently mount the wall receptor (see "Mounting the Wall Receptor").

Floor-to-Ceiling Tubestand/Wall Receptor Alignment

Aligning a floor-to-ceiling tubestand to a wall receptor is similar to the tubecrane alignment procedure.

To align a tubestand:

1. Mount and secure the ceiling (or wall) track.
2. Mark the floor using a plumb bob referenced to the upper track and lay floor track on the floor, but do not fasten.
3. Level the tubestand column vertically along entire length of track using a four-foot level. Check for level in both the front-to-back and side-to-side directions.

4. Once vertical column is level, check the level of the horizontal arm which holds the x-ray tube, and adjust the bearings so arm and x-ray tube are level.
5. Angle the tube to the wall where the wallstand will be located. Turn the collimator lamp on and make a mark on the wall at the center of the projected crosshair.
6. Run the tubestand along the entire length of the track. Notice if the light field drifts off of the mark. If the projected crosshair stays on mark, then the alignment is completed, and the floor track can be permanently fastened to floor.
7. If the light field drifts from the mark, recheck the alignment of the upper and lower track. If correct, then the last adjustment to be made is to the tubestand rotational detent.

Mounting the Wall Receptor

The wall receptor should be permanently mounted now that the x-ray tube axis has been established. Since the tube has been aligned to the wall, mounting the wall receptor is a simple process:

1. Angulate the tube toward the wall where the receptor will be located.
2. Turn on the collimator light.
3. Position the center line of the wall receptor at the center of light field.
4. Verify tracking and secure the wall receptor to the floor and wall.

Wall Receptor Adjustments

The wall receptor should be checked for smooth vertical travel. The image receptor assembly should move up and down with little effort. If difficult to move, the engineer should check the counterweight assembly. The correct number of lead counterweights must be installed for smooth vertical movement. When adding weights, the installer should make sure that image receptor (DR panel or CR cassette) is in place to achieve the correct counterbalancing.

The vertical lock assembly (friction lock or electromagnetic) should be inspected now and adjusted, if necessary. If being used, the reciprocating grid should be tested following the procedure described later in this chapter.

Aligning and Mounting the Table

Once the tube support and wall stand have been permanently mounted, the table can be brought into the room, positioned, and then permanently fastened to the floor. The tabletop should be removed for this procedure since the point of the table alignment is to match the x-ray field to the table image receptor. By removing the tabletop, the light field can shine directly on the receptor for an exact alignment.

The goal for installing the table is to have the center of the table receptor perfectly align with the center line of the wall receptor. The installer will move the table to match the tube/receptor axis, which has been established:

1. Position the tube at 40″ from the tabletop and center it to the receptor. Make sure the collimator is locked in its rotational detent. Energize the locks on the tube support except the longitudinal lock. Turn the collimator lamp "on."
2. Check the table receptor to see that it is not rotated in respect to the light field. If rotated, the installer should adjust the bearings on the receptor assembly.
3. Move tube and receptor together toward foot end of table. Slightly move the table at the foot end until the light field and receptor match. Next move the tube and receptor to the head end of the table. If the light field does not track with receptor, slightly "nudge" the table to achieve alignment
4. Continue to repeat step #2 until perfect tracking is achieved.
5. Mark the table location and permanently fasten.

Table Adjustment

While the tabletop is removed, the service engineer should perform the table adjustments. In fact, most table maintenance can be performed more accurately and with greater ease with the top off. Items to be adjusted include the receptor assembly, the electromechanical locks, the table travel limit switches, and the motor drive assemblies.

If a reciprocating grid is used, it should be inspected visually and audibly. The movement of the grid should be relatively quiet and smooth. The tabletop electromagnetic locks (and wiring) should be visually inspected before replacing the top. Once the engineer has completed the visual inspection, the tabletop should be replaced and the lock adjustments checked. The tabletop should move easily in all directions with the locks released. A grinding or scraping sound could indicate a lock that is dragging or misaligned. If a lock is, in fact, dragging, the distance between the lock and the contact surface (i.e., the metal strip on the underside of the tabletop) should be increased. A lock that is not adjusted properly can easily be detected by the loud humming sound that it makes. Any locks that fail to operate should be replaced at this time.

All the mechanical parts of the table vertical drive system (i.e., gears, chains, and belts) should be checked and adjusted, if necessary. Also, all bearing adjustments should be checked. The table should drive smoothly up and down with no apparent strain on the motor. The drive system for tilting tables, including all gears, belts, and chains, should also be inspected at this time and adjusted for smooth operation.

The limit switches for up/down and tilting motion should activate at the correct distances as specified by the manufacturer. Some tables provide an exposure position at a point midway between the full up and down position. This exposure position should be adjusted in conjunction with automatic collimation, if that option is available. Any safety interlocks for the table drive should be checked for proper operation.

CALIBRATION AND ADJUSTMENT

Installing a radiographic room is not a simple task. Installations are physically demanding and often involve working long hours, working often at nights and on weekends. In addition to the moving and lifting of heavy equipment that is required, the installer must pull, cut, crimp, "ring out," terminate, and label countless wires (sometimes in the hundreds). Equipment wiring is tedious work, often performed while lying on the floor, behind equipment cabinets or up in the ceiling. This type of work can take a heavy toll on the service engineer and a change of pace is welcomed.

The next phase of the installation is the calibration and adjustment phase. The goal now is to get all the devices in the radiographic room programmed and calibrated to the manufacturer's standards. During this phase, the rotor controller is adjusted, the radiation output is calibrated, the collimator is aligned, DR and CR systems are calibrated, and the AEC (Automatic Exposure Control) is adjusted.

It is often the case that if a piece of equipment is going to fail it will happen during the calibration and adjustment phase. When calibrating the x-ray outputs, for example, many exposures must be taken often at near maximum tube and generator ratings. Moreover, the tube support and image receptors are repeatedly maneuvered during the adjustment phase. When this stage of the installation has been completed, the room will be ready for use.

The priority of this phase is to get the x-ray tube calibrated, since x-ray exposures will be taken when adjusting the collimator light field and when calibrating DR and AEC circuits. Calibrating the x-ray tube now will ensure that the tube is being operated safely during those adjustments. Before starting the calibration, however, two important steps must be taken. First, the rotor controller must be properly set up, and second, the x-ray tube must be warmed-up. If these steps are not taken, a stable calibration will not be achieved and, even worse, possible tube damage could occur.

Starter Verification

As stated in Chapter III, a rotating anode is basically a split phase induction motor consisting of a stator (stationary electromagnets) and a rotor, which rotates inside of the stator. The rotor controller, or "starter," is a device that controls the rotation direction and speed of the anode in a rotating anode tube. It is basically a single-phase AC power supply that supplies current to the three stator windings: stator main, stator phase-shift (start), and stator common.

As with all single-phase induction motors, the main winding and the start winding must be out of phase to initiate rotation. To achieve this phase relationship, a capacitor is placed in series with the start winding at the rotor controller. The degree to which the main and phase-shift windings will be out of phase is directly related to the size of the capacitor used.

A Low Speed Starter operates by applying a starting voltage (approximately 100-240 VAC) to both the main and phase-shift windings of the stator. The current in the phase-shift winding, which has a capacitor in series, leads that of the main winding (see Figure 12). The current moving through these windings, by induction, forces the anode to rotate and accelerate up to the correct speed (approx. 3,300 RPM). After the preset time, the anode will be rotating at the proper speed and the starter supply is then switched, through a set of relay contacts, to a running voltage. This running voltage, of approximately 40–80 VAC, is used to maintain rotation of the anode until the exposure is completed. At the end of the exposure, the tube coasts down slowly until it stops.[8]

Starter verification consists of first measuring the start and run voltages (preferably with an oscilloscope to observe the phase shift) and comparing the voltages with the manufacturer's recommendations. Once this is done, the rotational direction of the anode must be verified. Ideally, the actual rotational speed should be measured with a vibrating reed tachometer. As the name implies, it measures the speed by sensing the frequency of vibrations in the x-ray tube housing and then displaying the value in rpm's. The "reed tach" is place directly on the tube housing during the boost and run cycles and the actual speed of the anode is read by the engineer. This measurement is very important because if the tube is not rotating at the correct speed, the heat rating of the tube will be reduced and target damage can occur.

The rotational speed can be adjusted by the service engineer. Adjustment is accomplished by increasing or decreasing the "boost time" (i.e., the time that starting voltage is applied to the stator windings). Another way to adjust anode speed is by increasing or decreasing the starting voltage.

8. A DC brake is used in high speed starters only. Its purpose is to quickly reduce the speed of the anode so that it will not rotate through the resonant frequencies of the x-ray tube. If the anode rotates at resonance, damage will result to the glass insert. Resonance is never reached with low speed operation.

Conditioning an X-ray Tube

X-ray tubes that have not been energized for an extended period, must be conditioned (or seasoned) before they can be calibrated and then used on actual patients. A tube that has been stored for as long as one month will develop an imbalance of internal charges along the inside surface of the glass insert. This charge imbalance will result in erratic exposures, making it impossible to achieve a stable calibration or consistent exposures.

The purpose of "seasoning" a tube is to realign the distribution of electrical charges within the glass envelope so they are properly matched to the x-ray system. When the correct distribution has been established, the output of the x-ray tube should be stable and the service engineer can then proceed with the x-ray calibration. Again, skipping this important step could result in permanent damage to the x-ray tube.

Furthermore, the x-ray tube must be at or near room temperature before proceeding with the tube seasoning procedure. This can be an issue during the winter months if, for example, a replacement tube was ordered because the original tube failed. In this case exposures should not be taken until the temperature of the x-ray tube stabilizes to near room temperature.

If the engineer is under time constraints to get the room operational, the tube can be warmed-up more quickly by connecting the high voltage cables and the rotor cable, and then powering-up the x-ray unit. With the generator power on, the equipment will be in a standby mode, in which case the selected filament of the x-ray tube will have a small amount of current flowing through it and will be dimly lit. The heat given off from the filament will help warm up the tube internally. While in standby mode, the engineer should alternately select between large and small focus at the x-ray control so that both filaments will be heated.

If pressed for time, the engineer can select a low technique on the console, press and hold the prep button for several seconds, and then release the prep switch for 30 seconds–no exposure taken. By performing this procedure, the filaments are raised to a higher temperature which adds heat to the tube. In addition, the process of boosting the tube also energizes the rotating anode which helps introduce heat into the tube housing. The "prep and release" cycle should be repeated for several minutes while the engineer alternately selects the large and small focuses.

The engineer should periodically check the temperature by placing his or her hand directly on part of the housing. When the housing temperature approaches that of the room, exposures may be taken at very low techniques–usually spaced one minute apart. After these steps have been taken, the tube should now be ready for the seasoning procedure.

The actual process of tube seasoning involves taking successive exposures starting at a low kVp (at a low mA setting) and slowly raising the kVp to maximum value. It is always recommended to follow the x-ray tube manufacturer's guidelines for conditioning an x-ray tube; however, a general tube seasoning procedure that will safely work for radiographic tubes is provided below. (Note: the tube current should be monitored during this procedure to ensure that it is within safe operating limits-see calibration.)

1. Select the lowest mA station possible for large focus.
2. Select 60 kVp and an exposure time of 1/4 second (250 ms).
3. Take three exposures–30 seconds between exposures (observe the mA waveform).
4. Repeat this process increasing by 10 kVp until maximum kVp is reached.

If arcing occurs at any point in this procedure, back up to the previous kVp setting and repeat the exposure sequence. When tube seasoning is completed, the x-ray tube calibration can be performed. If for any reason the x-ray tube cannot be calibrated directly following the tube seasoning procedure (e.g., if hospital personnel are in the room, lunch time, etc.), a tube warm-up is recommended before starting calibration.

Tube Warm-up Procedure

If the x-ray tube has been idle for four hours or more, it should be warmed-up before it is calibrated (or used on a patient). During the tube warm-up procedure, exposures are taken using a low technique that will slowly apply heat to the entire surface of the target. Once the target is sufficiently heated, it can be safely operated using higher techniques. Also, by warming up the tube before calibrating, a more stable calibration will be achieved. As a rule, a daily tube warm-up procedure will help promote longer anode life.

If a cold target is “hit” with a high technique exposure, the resulting tube current will quickly heat the area of impact on the target to a very high temperature. As a result, a large contrast in temperature now exists between the impact area and the rest of the target surface which is cold. The extreme variations in temperature across the surface of the target causes a condition known as “thermal stress.” Thermal stress will cause cracks or pits to form on the target surface, and may cause the anode to become warped. If the tube is used in this condition, erratic exposures will result and more damage could possibly occur to the x-ray generator. An x-ray tube that has a damaged target must be replaced.

The warm-up procedure is simply a shorter version of the tube seasoning procedure and is listed below:

1. Select the lowest mA station for large focus and 1/10 second exposure time.
2. Take one exposure every 30 seconds at: 80 kVp, 90 kVp, 100 kVp, and 120 kVp for a total of four exposures.

This procedure is sufficient to warm up most diagnostic x-ray tubes. When used daily by the x-ray technicians, this will absolutely increase the life of the x-ray tube.

Calibration Measurement Techniques

Once the x-ray tube conditioning has been completed, the service engineer can proceed with the x-ray tube calibration. An accurate calibration ensures that the x-ray tube will operate safely, and to specifications. Furthermore, a calibrated x-ray system will precisely deliver the exact parameters set at the control console, which is a requirement regulated by the DEP (Department of Environmental Protection) and BRH (Bureau of Radiation Health). Finally, a properly calibrated x-ray system will deliver consistent exposures, which will produce optimum diagnostic quality images at exposures entrance doses that are safe for patients.

To calibrate an x-ray system, the service engineer must obtain accurate measurements of the three main factors controlling x-ray dose: x-ray tube voltage (kVp), tube current (mA), and exposure time (t). The service engineer will take an exposure, observe readings from the test meters, and then make corrective adjustments so that the nominal values that are set on the x-ray control will agree with the actual values recorded on the test equipment. The measurements of kVp, mA, and time can be obtained in two distinctly different ways: invasively or noninvasively.

Invasive vs. Noninvasive Measurements

Invasive measurements are obtained by inserting the test equipment directly "in circuit" to measure the actual tube current (mA) passing through the tube, and the actual peak kilovoltage (kVp) that is applied to the x-ray tube. With invasive measurements, the test equipment is connected in series with the x-ray tube; consequently, the values obtained by invasive measurements will be the most accurate since they represent the exact voltage and current that the tube is actually "seeing." Because of this accuracy, a calibration made with invasive measurements has always been the preferred method, historically, in x-ray servicing.

Noninvasive measurements, on the other hand, are made by placing a radiation detector directly in the path of the x-ray beam. The detector senses and filters the radiation output exiting from the x-ray tube and then calculates the x-ray tube voltage, mR output, and time from the resulting radiation waveform (tube current is not normally measured using noninvasive means). Technically, what is being measured is the x-ray tube output and not the actual voltage applied to the tube. Since the noninvasive method calculates values based on the output radiation, and invasive methods measure real current and voltage, they do not always match exactly. However, the two types of measurements generally are within allowable tolerances so that noninvasive measurements have become the preferred method by service engineers and radiation physicist, alike. Today, solid state detector technology has improved to the point to where noninvasive detectors have become widely accepted for use during calibrations. Since most regulatory testing is performed with noninvasive test equipment, it makes sense for the service engineer to calibrate systems using this method.

One reason for the dissimilarity between the two ways of measuring kilovoltage relates to the fact that noninvasive measurements are greatly affected by many external factors. Those factors that most influence noninvasive measurements are detector positioning and the quality of the x-ray beam. Moving the detector to slightly different locations within the radiation field can affect the final measurement values. It is best, therefore, to always use a standard setup for testing and calibrating x-ray outputs. In the past early detectors had difficulty sensing radiation from x-ray units with lower outputs, such as portable units. Again, new technology has helped to overcome this obstacle.

The good news is that most x-ray generators manufactured today are high-frequency generators that allow for precise and accurate feedback measurements. As stated earlier, the most accurate calibration will be achieved with invasive test equipment. The feedback loops employed in high-frequency generators are used to precisely control kV, mA and time. Moreover, calibration test points are provided in the feedback circuitry to allow the service engineer to view the actual kV and mA waveforms. There is no need for invasive measurements. With these digitally controlled generators the engineer can calibrate the x-ray outputs by viewing actual representative waveforms from the provided test points while measuring the radiation outputs noninvasively.

An advantage to viewing the actual kVp and mA waveforms on an oscilloscope during the calibration is that any abnormalities observed in the waveforms can be identified and noted. This is important because any problems can be repaired while the equipment is new and still under warranty. It is of the utmost importance for the engineer to know that the equipment is operating at its optimum level and that all the x-ray waveforms are correct at the time of installation.

Invasive Measurements

Since some equipment manufacturers still recommend invasive measurements at the time of installation, a general procedure is outlined below. Two means of invasive measurements are commonly used. One invasive measurement test setup utilizes a High Voltage Divider (or High Voltage Bleeder) connected in series with the x-ray tube and is used in conjunction with a digital oscilloscope. With this setup, both anode and cathode waveforms can be viewed and measured. Also, the actual tube current passing through the x-ray tube can be directly measured directly.

A second method utilizes a series/parallel setup (Figure 32) in which the anode side is connected in series and the cathode side is connected in parallel. The parallel connection is done to eliminate any filament loading effects caused by the resistance built into the test equipment, which can alter the tube current reading. If an additional set of high voltage receptacles is provided on the high voltage transformer, and is not being used, the high voltage test device can be set up in a series/parallel configuration by activating the second set of wells. This series/parallel set-up enables the service engineer to view both cathode and anode waveforms while calibrating without loading the filament circuit.

With the series/parallel setup a Digital mA/mAs Meter is needed. The digital meter displays the DC mA value. The mA/mAs meter is connected in series with the mA metering circuit of the x-ray generator, usually found at the midpoint (M1 + M2) of the high voltage secondary (refer to Figure 4).

The digital mA/mAs meter has two modes of operation. In the mA mode, the meter reads the tube current (mA) in "real time" during to exposure. The problem with using the meter in this mode of operation is that long exposures of approximately one second are required in order to obtain a stable mA reading. If a complete calibration was performed using the mA mode only, the x-ray tube housing would eventually overheat. In addition, the tube exposure limits would be exceeded at the higher mA stations and exposures would be blocked. Consequently, this mode can only be used for the lower mA stations (i.e., 25 mA, 50 mA).

To avoid any possible damage to the x-ray tube, the second mode of operation, the mAs mode, should be used when calibrating the higher mA stations. In the mAs mode, the meter reads the product of mA and time (mA x seconds or mAs) and then displays the result. The service engineer will set a time on the x-ray control that will make calculations simplified. For example, at 100 mA setting a time of 0.10 seconds achieves 10 mAs (100 mA x 0.10 s = 10 mAs). In addition, the mA/mAs meter is designed to hold the most recent mAs reading on

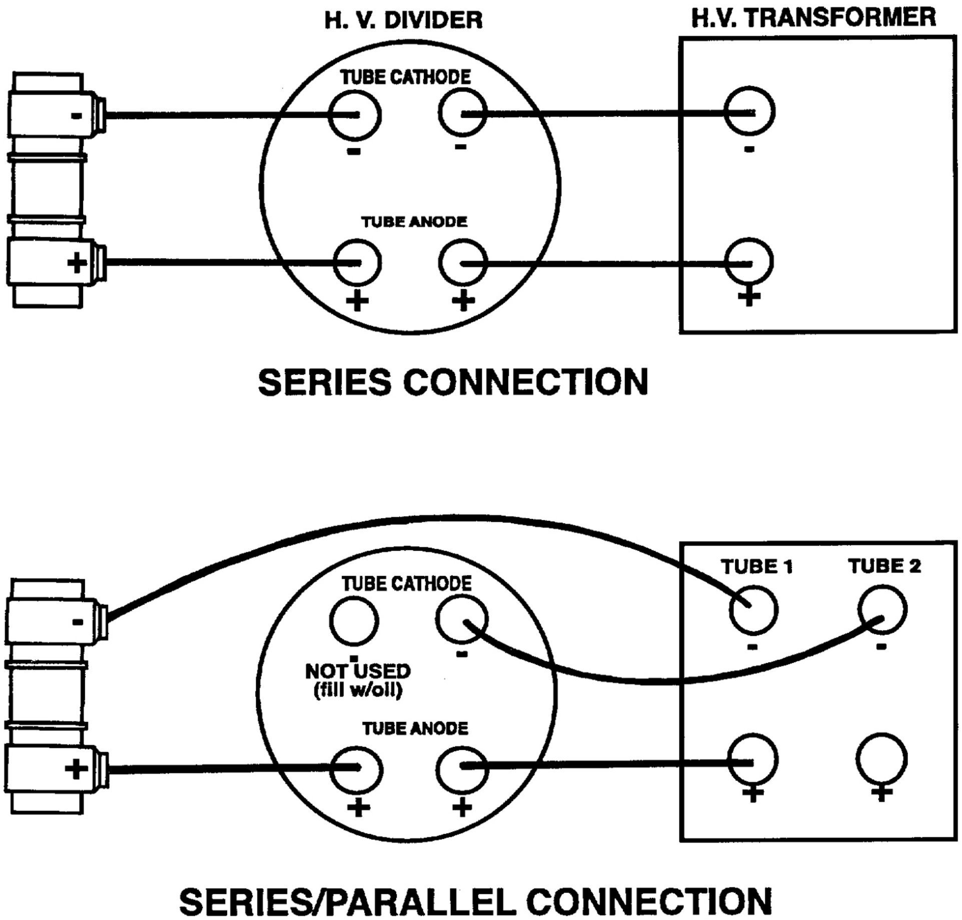

Figure 32. Connecting a high voltage divider. The series/parallel connection allows for viewing the cathode kVp waveform without introducing a load factor to the x-ray generator.

the display until the next exposure is taken. Most service engineers own an mA/mAs meter because it is inexpensive, easy to use, and reliable.

If calibrating invasively, the engineer should take the extra step and place a noninvasive kVp meter in the radiation field to compare the results with those obtained invasively. With the minor differences noted, the noninvasive meter can now be used with confidence for calibration checks. Additionally, the service engineer should confirm the accuracy of the mA panel meter located on the x-ray control. He or she should compare the readings obtained with the test meter to those of the panel meter. This is done so that if an mA calibration check is needed during a service call, the engineer can rely on the panel meter with confidence, thus saving valuable time.

What Is Being Calibrated?

During an x-ray calibration, three parameters are adjusted by the service engineer: tube voltage (kVp), tube current (mA), and exposure time (t). The x-ray service engineer will adjust the kVp, mA, and time so that the values that are set on the x-ray control precisely match the actual values recorded on test meters. These three factors are controlled at the x-ray generator control and, consequently, all adjustments are made here, as well.

For the most basic x-ray generators, the amount of kilovoltage that will be applied to the x-ray tube is determined by the primary voltage selected at the x-ray control. This primary voltage (e.g., 100 VAC), when applied to the primary winding of the high voltage transformer, will be stepped up to the desired secondary voltage (e.g., 100 kVp) which is then applied to the x-ray tube. The actual values of primary and the corresponding secondary voltages can be obtained from the transformer characteristic graph for that high voltage transformer. The amount of tube current is regulated by a voltage that is applied to the filament transformer. When an mA is selected on the x-ray control, a corresponding voltage will be applied (during an exposure) to the appropriate filament winding of the x-ray tube. The filament is heated to the correct temperature to deliver the desired amount of tube current. Regarding time calibrations, only early vintage machines used timers that required adjustments. Today, all generators use digital timers to control the exposure time. The engineer will just verify its accuracy. No adjustments are necessary. If the timer is off, then the timer board is bad and should be replaced.

With calibration, however, the control of both the kVp and the mA is not straightforward. The kilovoltage applied to the x-ray tube does not remain constant through the entire range of selected mA's. In addition, tube current will vary with changes in kilovoltage. The reason for this relates to the fact that the tube voltage and tube current interact with each other. This interaction is attributed to two characteristic phenomena of x-ray tubes: the x-ray tube loading effect and the space charge effect.

An x-ray tube, like all vacuum tubes, does not represent a fixed load to the power source. Initially, the tube will appear highly resistive to the power source. However, once current begins to flow through an x-ray tube, the resistance of the tube decreases in direct proportion to the current flowing through it. If the current is high enough, the resulting low resistance of the tube will cause significant loading of the power source. This excessive loading, in effect, will "pull down" the supply voltage which then also reduces the kilovoltage that is applied to the tube. This is especially true for single-phase and three-phase generators.

The loading effect is magnified by the inefficiencies inherent in the design of transformers. All transformers experience two types of energy loss, termed IR losses and regulation losses. These losses are given off as a heat energy and result in a reduction in the output secondary voltages. The service engineer compensates for these transformer losses during calibrations by increasing the primary voltage as the selected mA is increased.

A Transformer Characteristic Curve (Figure 33) is provided for all high voltage transformers and is usually included with the service literature for each x-ray unit. This curve shows the relationship between the primary voltage and secondary voltage of the transformer under different loading conditions. From the curve, the service engineer can determine the actual primary voltages required to achieve a given kVp for each mA selection. The sample characteristic curve (Figure 33) shows that at 80 kVp there is a significant difference in primary voltage between 50 mA (120 VAC) and 300 mA (190 VAC). This chart provides valuable information that can be used during the calibration.

The second characteristic of x-ray tubes that affects the calibration relates to the regulation of tube current. When the filament wire inside the x-ray tube is heated, electrons will be "boiled off" of the wire by a process called thermionic emission. As the temperature increases, an "electron cloud" will form around the filament wire. This electron cloud, referred to as the space charge, will increase in size proportionally with an increase in the filament current.[9]

9. Filament current should never be confused with x-ray tube current, although they are closely related. Filament current, in the range of 1 amp to 6 amps, flows directly through the filament wire and heats the wire to "boil off" electrons. Since the number of electrons liberated dictates the amount of current that will flow through the x-ray tube, filament current controls x-ray tube current. X-ray tube current is in the milliamp range (i.e., 10 mA to 1200 mA).

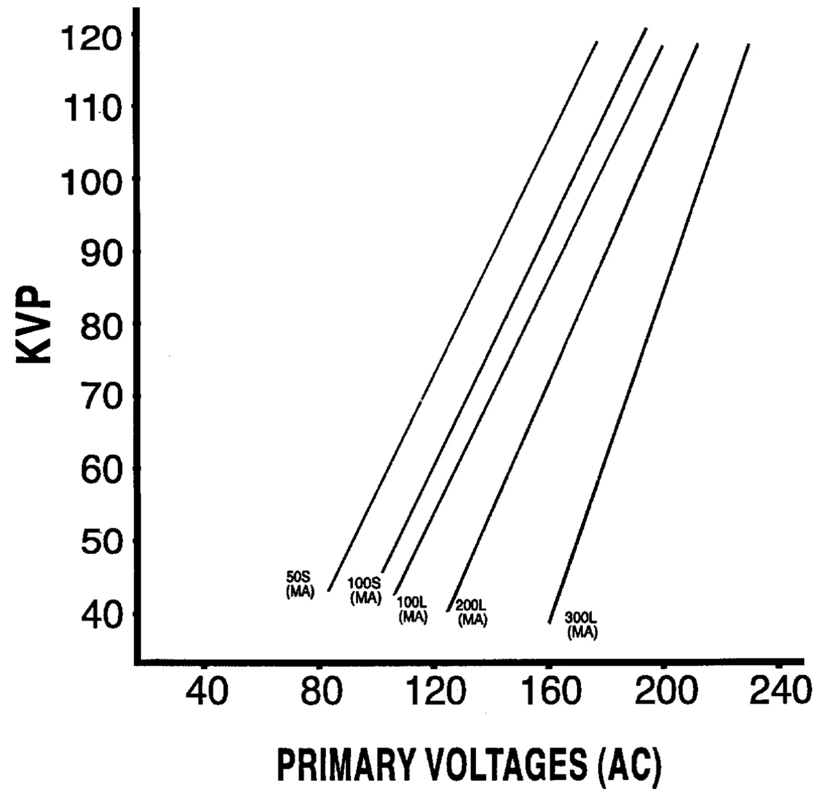

Figure 33. Typical transformer characteristic curve. Because of tube loading, a greater primary voltage is required at higher mA settings for a given kVp setting: 190 VAC for 300 mA verses 120 VAC for 50 mA at 80 kVp.

The space charge phenomenon is unique to thermionic vacuum tubes and greatly influences calibrations where high voltages are involved. At higher voltages, the electrons in the cloud become more strongly attracted to the anode (positive electrode) of the x-ray tube. As the kVp of the x-ray tube is increased, more of these electrons in the cloud are "pulled" toward the anode, thus causing an increase tube current. Specifically, at a given filament voltage (and corresponding space charge) there will be more tube current at 100 kVp than at 60 kVp.

Thus, x-ray generators, historically, had to provide a means to compensate for this space charge effect, which was adjusted during calibration phase. Space charge compensator circuit effectively lowers the filament voltage at higher kVp's and raises the filament voltage at low kVp settings. Newer digitally controlled high-frequency generators automatically account for the effects of tube loading and space charge so that calibrations have become much simplified.

X-ray Tube Calibration

A general calibration procedure for single-phase generator is provided below, followed by the more typical high-frequency generator calibration. The calibration procedure for single-phase x-ray generators is outlined here because it includes the important steps required for a complete x-ray output calibration. By carefully reviewing the entire procedure, the service engineer can better understand what is being accomplished during the x-ray calibration. Calibrations are much simplified with high-frequency generators and will be discussed next. As always, the service engineer should follow the manufacturer's guidelines when possible.

The basic procedure on a single-phase generator calibration consists of first checking the no-load primary voltages for each kVp setting. These voltages are usually listed in the service manual but can also be obtained from the transformer characteristic curve described above. Generally, the x-ray generator is configured at the factory so that it is wired internally to produce the correct no-load voltages once the incoming line is set. Then engineer simply verifies the correct voltages.

Next the service engineer will adjust each mA station so that the mA set at the control console is equal to the actual mA read on the test device. This preliminary mA adjustment is performed on a kVp station that is not affected by the space charge compensation circuits (usually 80 kVp). As a rule, large focus is always calibrated first, followed by small focus. Once the preliminary mA adjustments are completed, the space charge compensation circuits are adjusted for each mA station.

Some x-ray generators are designed in such a way that the mA calibration and space charge compensation are combined in one step. This is accomplished by calibrating each mA station at a low kVp point (60 kVp) and then at a high kVp point (90 kVp). The low and high kVp adjustment points essentially create a slope which automatically includes the space charge compensation so that the mA output will track over a range of kVp settings.

The actual means of adjusting the mA depends on the manufacturer's design. In the more basic generators, adjustment is accomplished by moving a sliding tap on a large, wire-wound resistor, usually rated at 100 watts, to increase or decrease resistance in the filament circuit. Changing the resistance, in effect, changes the voltage applied to the filament transformer thereby altering the filament current. Some generator designs use potentiometers instead of slider taps to accomplish the mA adjustments. Similarly, space charge compensation can be accomplished by a resistor adjustment, or by selecting different taps on a special boost/buck transformer which raises or lowers the filament voltage. With the later generator designs that utilize digital control for kVp and mA regulation, adjustment is accomplished by using potentiometers or by soft key control at the console.

With mA calibration completed, each kVp setting is checked and adjusted for each of the mA stations. Adjusting the kVp on single-phase generators is accomplished by moving taps on resistors, adjusting a potentiometer, or through software at the keypad of the control.

With single-phase generators that have an analog kVp panel meter, what is being adjusted is the kVp prereading of the kVp meter. An 80 kVp reading on the panel meter, for example, is simply a representation of the corresponding primary voltage selected by the kVp major and minor tap switches. Here the goal of kVp calibration is to adjust the kVp indication on the display to match the actual kVp delivered to the x-ray tube. With kVp and mA outputs adjusted, the installer verifies that the exposure times are accurate. As said, the timer circuits of today do not require adjustment.

Finally, the engineer should also monitor the line voltage supplied to the generator. A significant drop in the line voltage during an exposure would indicate a deficiency in the power line supplied to the x-ray generator. This step is crucial to the performance and longevity of the radiographic equipment. It is important to note that the manufacturer will only guarantee the output accuracy of the x-ray generator if the line regulation is within their specifications. Consequently, the line voltage regulation must be measured and recorded in the installation manual. The measurement should be made after the completion of the x-ray calibration, since line regulation is tested at near maximum generator output. Most manufacturers of radiographic equipment require a 5 percent line regulation.

To measure line regulation, the line voltage is first measured while the machine is idling in "standby mode" (no-load). A second measurement of the line is made during an exposure at (or near) maximum generator technique (load). The percent of line regulation can be determined by using the formula: % regulation = $(V^{no\ load} - V^{load})/V^{load}$.

High-Frequency Generator Calibration

The calibration of an x-ray generator, historically, has been performed in the manner described in the previous section. The procedure works for most x-ray systems other than high-frequency generators. With high-frequency generators, the x-ray tube calibration procedure is greatly simplified, requiring fewer exposures and adjustments. These generators produce an output waveform that approaches a pure DC square waveform, with very little ripple. High-frequency generators precisely regulate the radiation output, far better than any other x-ray generator, marking a major advance in equipment design.

To calibrate a high-frequency generator, the installer needs to verify that the generator is correctly wired for the incoming power line and check that the operating voltages are to specification at key test points within the x-ray generator power section. With those checks, he or she can begin the kV and mA calibration. Stated briefly, the central concept of high-frequency calibrations is focused on obtaining a square output waveform.

Figure 34 shows the typical waveform for both mA and kVp (or simply kV, which has become the accepted terminology used with these generators). The first image shows the desired wave shape: a perfect square wave. The square wave represents the fast switching of the x-ray radiation output. With the exposure start command, the kV (and mA) waveform rises instantly to the level set at the control, remains at that level for the set exposure time, then abruptly switches off. The goal of the installer is to calibrate the generator to achieve that square wave output.

The first adjustment is what is termed the mA preheat adjustment. This adjustment sets the leading edge of the tube current waveform. Here, we want the filaments of the x-ray tube to heat to the proper level so that a perfect mA calibration can be achieved. The mA preheat adjustment varies the leading edge of the square wave up and down so that the exposure begins at the correct mA level and then remains at that level for the entire exposure. For the adjustment, the installer takes an exposure at a mid-range setting for kV and mA and observes the waveform on an oscilloscope. If the waveform displays overshoot (Figure 34), the circuit is adjusted down until a flat waveform is obtained. If undershoot, the installer adjusts to bring the leading edge of the waveform up. Adjustment is often accomplished by "tweaking" a potentiometer. Many designs use digital control to set the preheat where a DAC value (Digital to Analog Converter value) is adjusted at the console. When a square waveform is obtained for the mA preheat setting, then engineer can repeat the adjustment for a second focus on the x-ray tube if present. Large focus is always performed first, then small focus.

If the generator employs a closed-looped design, the rise time of the kV waveform must be adjusted. Closed-loop circuitry employs feedback to control the kV output. During the exposure, the kV signal is sampled and compared to the set value. The feedback circuitry responds to any variance in the set vs. actual values and applies a correction. With a closed-loop design, the installer will adjust the rise time (or speed) of the kV circuit to achieve a square waveform. The leading edge of the kV waveform is adjusted up or down so that the waveform is flat at the start of the exposure–just like with the mA preheat adjustment. For example, at the 80 kV setting, we want the kV output signal to rise to the 80 kV level instantly and remain at that level for the entire exposure. This adjustment can involve changing capacitance in the kV loop to alter the speed of the rise time.

With the leading edge of both mA and kV waveforms calibrated, the overall levels of each kV and mA setting can be adjusted to match

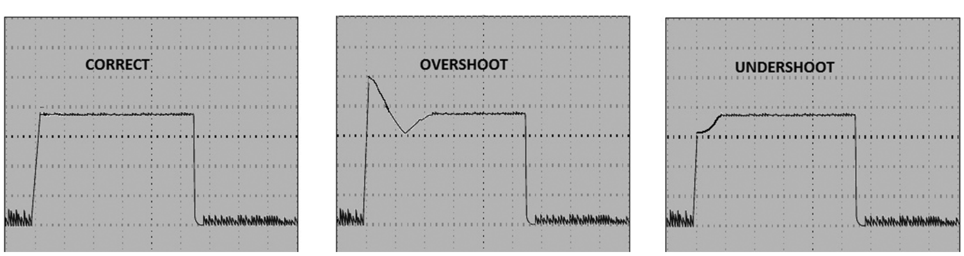

Figure 34. High-Frequency Generator Square Wave Adjustment.

the values that are set on the console. During the calibrations, the kV and mA waveforms are monitored with an oscilloscope at test points within the x-ray generator, while the engineer measures the x-ray tube outputs with a noninvasive test instrument. The service engineer adjusts each setting, individually, so that the outputs match the setting on the console.

The above procedure represents a complete calibration for high-frequency generators. The procedure is simple and the calibrations are very exact. Digital technology has made the task of calibrations much easier for the service engineer. But there is even more good news. Many x-ray units provide an "autocalibration" mode. The installer enters into the autocalibration mode through the service menu at the console, initiates the calibration by depressing the exposure switch, and holds the exposure switch until the calibration has been completed. During the autocalibration, the generator automatically takes exposures, monitors the resulting waveforms with its feedback circuitry, and makes minor corrections as needed. With these units, the installer simply verifies the outputs with a noninvasive test device when the autocalibration is complete.

Collimator Adjustment and Alignment

When installing a collimator, the service engineer must perform several operations to ensure that the collimator is accurately limiting the size of the radiation filed to the image receptor. For manual collimators:

1. The intensity of the light field must be verified.
2. The light field must be made to match the x-ray field.
3. The cross-hair window must be aligned.
4. The centering light must be aligned to the image receptor.
5. The SID indicator must be adjusted.
6. The field size indicators must be verified.
7. The correct amount of filtration must be verified.

It is critical that these checks and adjustments are performed correctly. If the collimator is not adjusted properly, the patient could receive significantly more radiation than is necessary for that exam, and the x-ray staff could be exposed to off-focus and scatter radiation.

Also, if the light field and x-ray field are not properly aligned, certain anatomy of the patient may be "cut-off" of the final image. When this occurs, the technician must repeat the exam, which increases the dose delivered to the patient and wastes time.

A setup procedure for manual collimators is provided below.

Light Field Intensity

An important function of the collimator is to produce a light field that accurately defines the x-ray field. Most collimators use high output halogen lamps to create a bright light field. Newer designs utilize LED technology. The standard for collimators is that if a "light localizer" is to be used to indicate the x-ray field, it must have a minimum intensity level so that the light field produced will be clearly visible in normal room lighting. Specifically, the minimum average illumination should be not less than 160 lux (15 foot-candles) at 100 cm (40″) or maximum SID, whichever is less. Collimator field lamp output is measured with a light meter (photometer) that is placed at the center of the light field. Most collimators today will easily meet this minimum requirement, but an installer should nonetheless measure the light output level at the time of installation.

Light to X-ray Field Congruence Test

As said, one of the important functions of the collimator is to project a light field onto the image plane that gives a visual indication of the x-ray field. The edges of the light field must therefore match the edges of the x-ray field to within specified limits. The procedure for testing this congruence is described below.

1. Position the tube 40″ above the tabletop and place an image receptor (CR plate or DR panel) on the tabletop. The x-ray tube should be at 0° angulation.
2. Center the receptor to the light field and close the collimator shutters down to an area of 10″ by 10″.
3. Mark the edges of the light field with some type of metal marker that will produce a sharp border on the image.
4. Take an exposure using a technique that will be of adequate density to see the markers.

5. Measure the difference between the edges of the light field (as indicated by the image of the markers) and the actual radiation field.
6. The sum of the difference for the long axis and the sum of the difference for the cross axis should not exceed 2 percent of the SID.
7. Adjust the light field if necessary and repeat this procedure until it is within the specified limits.

The two directions that the lamp can be adjusted are in the longitudinal direction and in the transverse direction as referenced to the tabletop. Generally, the lamp bracket which holds the lamp in place is moved to correct errors in the long direction. The field lamp mirror, which is found in all collimators, is adjusted to correct errors in the transverse direction. If the mirror assembly is the stationary type, the cross-adjustment is also made with the lamp bracket.

Cross-Hair Window Adjustment

This adjustment is for centering the cross-hair pattern that is projected from the collimator onto the image plane. The cross-hair pattern is used to precisely align the x-ray tube to the patient and receptor. The plastic window, located in the bottom of the collimator, is etched with a cross-hair pattern. When the collimator lamp is lit, the cross-hairs are projected to the image plane. The latest designs use a laser light to project the cross-hair pattern onto the image plane.

When the cross-hair is etched on the plastic window, adjustment is easily accomplished by loosening the screws that hold the plastic window in place and centering the cross-hair pattern within the light field. A quick method for checking if the cross-hair is properly centered is to close the collimator blades down slowly, one set of blades at a time, until a narrow line of light is projected. This narrow light line should be positioned at the center of the cross-hair. With lasers, centering is accomplished by positioning each laser's projection to the center of the light field.

Collimator Centering Light Adjustment

Many collimators provide a centering light that allows the technician to align the x-ray tube precisely to the image receptor to ensure that the receptor is being exposed. Since the image receptor is hidden within the grid cabinet assembly, the technologist needs a means to confirm proper centering. The light source for centering is usually derived from the collimator field lamp and is projected to the front of the image receptor assembly using a prism or mirror. By adjusting the prism/mirror assembly, the light-line can be centered to the receptor. The service engineer should always check the adjustment by taking an exposure.

SID Indicator Set-up

Collimators provide a means to identify the Source to Image Distance, or SID. The SID is the measurement of the distance from the focal spot (the source) of the x-ray tube to the image plane. For each x-ray examination, there is a specific SID that provides an optimum image of the desired anatomy. Forty inches is common SID for many studies; however, 72 inches is preferred for chest exams. The SID indicator on the collimator must be accurate since the x-ray technician will use this reading during each setup for an exam. Also, a specific SID must be used when a focused grid is used. Using an SID different from that stated on the grid will result in grid lines on the image (see Chapter V). In addition, if the SID indication is not accurate, the field size indicator on the collimator size adjustment knobs will not be accurate.

In the most basic collimator design, the device used for SID indication is usually a metal tape measure that attaches directly to the collimator housing. The tape measure has been modified to indicate the tube focal spot to image plane distance. The x-ray technician can obtain accurate SID readings using this measuring tape. Some collimators provide a digital display to indicate the SID, other types use a "ready" lamp indicator when the tube is positioned at the correct SID.

If the SID indicator is not included with the collimator, it is usually provided with the tube support assembly. Here the SID indication will consist of a graduated scale that ranges from 36 to 72 inches. This SID scale attaches directly to the vertical tube column to indicate vertical SID. A second graduated scale is attached along the ceiling rail to indicate horizontal SID. If an automatic collimator is being installed, interlock switches will be positioned at the 40 and 72 inch SID marks to satisfy the collimator logic.

Verifying the SID Indicators

To set up the SID indication properly, the x-ray service engineer must know the exact location of the focal spot within the x-ray tube housing. The information regarding the focal spot location (with respect to the housing port) can be obtained from the manufacturer of the x-ray tube. Some tube manufacturers provide a mark on the end cap of the x-ray tube to indicate the focal spot location. This mark, however, should be verified by actual measurements.

1. Position the tube 40″ above the image plane as measured from the focal spot and lock the tube in place.
2. If the collimator is equipped with a modified tape measure and if the correct number of spacers were added when the collimator was mounted, the tape measure should now also indicate 40″ to the image plane.
3. Mount the switch and switch activator (for 40″ SID) on the tube column if used.
4. Place a graduated scale (if supplied) on the tube vertical column to indicate 40″ SID to image receptor.

Once the vertical SID indication is verified, the horizontal SID indicators can now be set by using the same mark on the end cap of the tube, which is known to be accurate. The SID setup procedure should be performed as described above for both 40″ and 72″ horizontal SID's.

Field Size Indication

A requirement of all collimators is to provide an indication of the x-ray field size for the SID that is being used. The field size indicators are graduated scales that are mechanically attached to the shutter control knobs so that the size of the x-ray field can be directly read as the knobs are turned. The accuracy of the field size indicators can be verified by performing a simple test which is detailed below. For this test, the service engineer will set a specific field size by adjusting the shutter control knobs while reading directly from the scale on the collimator. He or she will then measure the actual field size of the light field.

To Check Field Size Indicator

1. Position the x-ray tube for 40″ SID to the table top.
2. Mark off a 10 x 10-inch square on the tabletop using a sheet of paper or masking tape.
3. Close shutters down until the indicator on the collimator reads 10 x 10 inches.
4. Turn on the collimator lamp and verify that the light field is 10 x 10 inches.

If there is a deviation of more than 2 percent of the SID, the indicators must be adjusted. Adjustment is usually accomplished by loosening the set screws that hold the scales to the longitudinal and horizontal shutter knobs. Once an adjustment is made, the field size testing procedure described above must be repeated.

Digital Panel Calibration

With the x-ray generator fully calibrated and the collimator adjusted, the image receptor can be calibrated. A DR panel calibration is outlined below. Digital panels require a computer and imaging software to process the raw image, to enhance and modify the image, and to view the image. Panel manufacturers install proprietary software on their computer that works specifically for their panels. A main function of the software is to take the raw x-ray data from the exposed panel and apply processing and enhancement to obtain a diagnostic quality image.

In addition, the software is used to fine-tune, or calibrate, the panel for optimum imaging. Every panel manufactured has slightly different electrical characteristics–and they all have minor defects due to the manufacturing process. The calibration sets the gain and offset of the panel, and, more importantly, removes the inherent defects as well as those defects that develop over time. Image defects such as bad pixels, or line artifacts that arise as the panel ages can effectively be removed with the software.

Though each manufacturer's panel calibration is slightly different, they all require a series of exposures taken at specific dose settings. The information gathered from the exposures is used to create a calibration curve for that panel. A typical panel calibration consists of acquiring dark images (no radiation), which are used to set the panel offset. Next, the panel is fully exposed with nothing in the radiation field (i.e., flat field) by a series of exposures, increasing the dose to near saturation to set the gain calibration. When the data from these exposures is processed, the software will effectively blank out bad pixels, set the null and saturation values so that panel will produce the best image quality. Most panel calibrations can be performed in less than 30 minutes.

X-ray Tube Focal Spot Measurement

With the x-ray tube and panel calibrations completed, it is a good time to measure the focal spot size of the x-ray tube. Even though x-ray tubes are fully tested before they are shipped, it is a good practice to make actual measurements for the installation record. For this measurement, a lead test star is commonly used. The test star is positioned in the x-ray field, exposed, and then measured. The test star produces a "spoked wheel" image as seen in Figure 35. The radiation from the actual focal spot of the tube will create a blurred region in the spoked pattern. The blurring is due to the penumbra of the focal spot. By measuring the length and width of the blurred region, the actual focal spot size can be determined using the formula: $F = N/57.3 \times D/(M - 1)$. Where: F is the focal spot size. N is the angle of the star pattern (written on the test star) and D is the diameter of the blurred region (L or W). M is the magnification. To perform the measurement, follow the instructions included with the test star.

The service engineer should perform an additional test to check the resolution of the entire system: from the x-ray tube to image receptor and viewing monitor. For this test a special resolution test tool (e.g., pie mesh or line-pair phantom) is placed between the tube and receptor and an image is taken of the phantom. Often, the resolution phantom is placed directly on the image receptor. The processed image is evaluated on the viewing monitor for image sharpness and contrast. This simple test is routinely performed by state and regulatory inspectors. The test images should be stored permanently on an external drive for good record keeping.

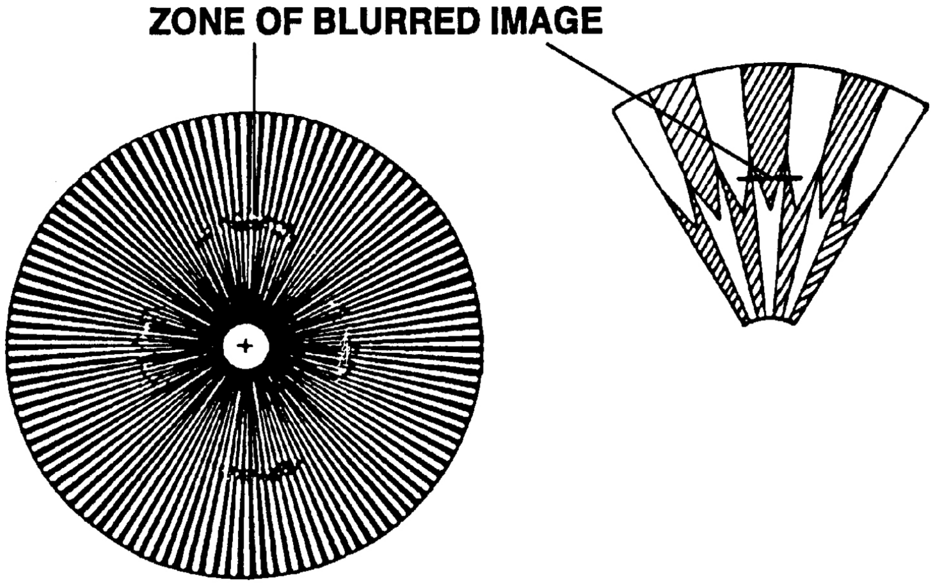

Figure 35. Lead test star image. Measurements of the blurred regions are used to calculate the focal spot size of the x-ray tube.

Automatic Exposure Control

An Automatic Exposure Control system, or AEC for short, is available as an option with most x-ray generators. AEC controls the exposure time automatically, achieving optimum image densities with every exam. An x-ray generator equipped with the AEC option can produce images that are more consistent in quality than one that provides manual techniques only. Also, since fewer "retakes" are performed in a room equipped with AEC, many technologists request this option.

With an automatic exposure control system, a detector senses the x-ray radiation delivered to the patient and then automatically terminates the exposure when the optimum image density is achieved (as set up by the installer). The x-ray technologist need only set the kV and mA parameters, leaving time to be controlled by the AEC. A backup time setting is required as a safety measure so that if the AEC fails to function properly, the x-ray unit will then terminate the exposure. The backup timer is usually set to a time that is much longer than the anticipated exposure time. A properly calibrated AEC unit will consistently reproduce optimum image densities regardless of the size of the patient.

An AEC unit consists of a detector and control unit. The detector or pickup, located in the image receptor assembly, senses the x-ray radiation that is delivered to the patient. The detector is connected through a shielded cable to a control unit which converts the detector output signal to an exposure stop signal that is sent to the x-ray generator timer circuits.

The Detector

Since the detector assembly is used to sense radiation, it must be placed in the path of the x-ray beam in the image receptor. The function of the detector is to sense x-ray radiation that has passed through the patient and convert that radiation energy to an electrical signal that is sent to the control unit where it will be used to control the exposure time. Historically, there have been three different types of AEC units used in radiography, each distinguished by the type of detector employed.

If the detector contains one or more photomultiplier tubes, the AEC unit is referred to as a phototimer. The phototimer was the earliest type of AEC unit, introduced by Paul Hodges, its designer, in 1942. It had such an impact on radiography and was so widely used that, today, service engineers often refer to any AEC unit as a phototimer.

The phototimer detector assembly consists of a fluorescent screen encased in a light-tight seal. The purpose of the fluorescent screen is to convert x-ray radiation to light energy. A "window" is provided at one edge of the detector to allow the light to exit. A photomultiplier tube, or PMT, is optically connected to the detector at the exit window and is used to convert the light energy to an electrical current signal which is amplified and sent back to the AEC control for further processing.

The PMT is a special type of vacuum amplifier tube that consists of a light sensitive photocathode, a series of dynodes, and an anode (see Figure 36). The photocathode converts light energy into a stream of electrons that will then strike the first dynode.

A dynode is a special electrode that is used for signal amplification. If one electron strikes the surface of a dynode, that dynode will emit 5–7 secondary electrons. Consequently, by using 9 (or more) dynodes

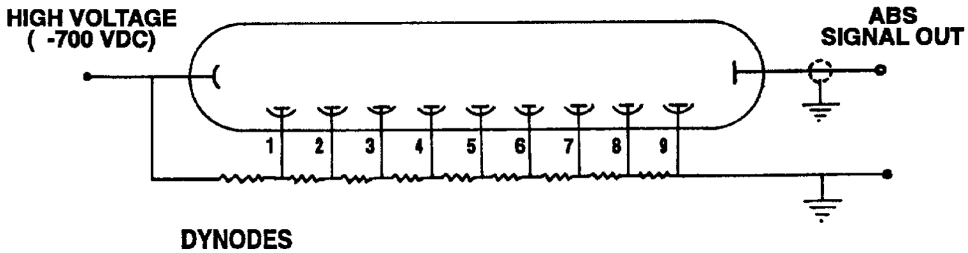

Figure 36. Photomultiplier tube (PMT). The dynodes are wired in series to achieve high amplification.

in succession, very high amplification can be achieved. The current signal is sent from the anode of the PMT to the AEC control circuitry.

The PMT was commonly used in the exposure control circuits of x-ray equipment because it provided very reliable, trouble-free operation. They do, however, require a high supply voltage (600 VDC to 1000 VDC) for operation. In addition, this power source must provide a regulated, noise-free output to achieve the optimum performance needed for consistent exposure control.

The second type of AEC detector utilizes an ion chamber instead of a PMT for signal conversion. The ion chamber is located within the detector assembly and is also positioned directly in front of the image receptor as in the case of the phototimer detector. Instead of performing light conversion, however, this detector utilizes the ionizing effects of x-ray radiation. When x-rays strike the ion chamber, they will ionize the gas within, producing an electrical potential across the chamber.

Usually, a preamplifier is physically attached to the detector assembly. The preamp provides the initial signal conditioning required before it is sent to the AEC control for further processing. Ion chambers require a regulated power supply voltage in the range of 300 VDC to 400 VDC. Generally, adjustments are provided in the preamplifier for balancing the outputs of each ion chamber. Otherwise, all other adjustments are performed in the amplifier section in the AEC control.

The third type of AEC unit, which is the most common type used today, utilizes a solid-state detector. A solid-state detector is an exit-sensing device that is usually positioned in the x-ray beam, just behind the image receptor. The sensor detects x-ray radiation that has passed through the patient and image receptor and sends a corresponding electrical signal to the AEC control unit.

The operating principle of the solid-state detector is very basic. If a diode, for example, is placed in the path of the x-ray beam, it will conduct current. The amount of current produced by the diode is proportional to the amount of radiation that strikes it. The solid-state detector utilizes this same principle for operation. It is virtually self-powered.

The advantages of this type of detector are its compact size and extremely rugged design. Most important, however, is that it is the only AEC unit that does not require a dedicated power supply to bias the detector. The small size of the solid-state detector makes it ideal for use in all radiographic modalities.

AEC Control

As stated, radiation, when striking the detector, is converted into a current signal. The output signal from the detector is integrated at the AEC control. After initial processing, the signal is converted to an analog voltage that is then fed to a comparator in the control. Here the level of the voltage is compared with a reference voltage. When the level of the detector signal matches the calibrated reference signal, an exposure stop signal is generated and sent to the x-ray control.

The actual value of the reference signal is adjusted during the AEC calibration and is dependent on factors that are selected at the operator control. These include the kVp setting, the density compensation selected, and the image receptor type. These parameters must be taken into consideration when the engineer performs the AEC calibration.

AEC Calibration

AEC calibration should be one of the last tasks performed on an installation. At this stage in the installation, every device is aligned and calibrated and fully functional. The equipment is, in fact, ready to be used on patients. The AEC calibration is the final step towards getting the best quality images from the new equipment.

The goal of AEC calibration is to achieve a desired optical density for the image receptor being used through the entire range of exposure techniques. The density should remain constant with all x-ray views and patient sizes. The calibration consists of establishing an optimum density for the image receptor, adjusting the amplifier gain and offset settings, balancing the detectors (for three field detectors), and applying a correction adjustment so that the densities remain the same over the range of kVp settings. Test equipment needed for AEC calibration consists of a homogenous radiographic phantom (usually acrylic) and a radiation meter.[10]

The radiographic phantom is used to simulate the density of an average patient. Phantoms are used because of the numerous exposures that will be taken during the AEC calibration. Although the phantom closely mimics human tissue, it cannot exactly produce the effects of an actual patient. Consequently, the service engineer may have to return to the facility to fine-tune the density adjustments after the equipment has been in-use for a while.

FINAL TESTING

With all the devices in the x-ray room calibrated and adjusted to specifications, the room should be ready for use. However, before the room can be turned over to the customer, two important tasks must be performed. Because of the numerous alignment and adjustment procedures that were performed by the service engineer(s) during the installation, it is possible that some items could have been overlooked. Also, because some of the adjustments interact it is very important to test the equipment as a complete system. Consequently, a final room checkout should be performed to ensure that all the equipment is operating as specified by the manufacturer. When the final testing has been completed, the room should be thoroughly cleaned.

The final check should be performed ideally by a senior service engineer who was not one of the actual installers. This is done to eliminate any bias that may be present when testing the room. All items in the room should be tested during the final room checkout. Below is a checklist that can be used for final testing. The service engineer can also use this same checklist as a final checkout after a preventive main-

10. Phantoms can be purchased from many x-ray accessory suppliers. Also, acrylic sheets can be purchased locally. Buy 1″ thick sheets and cut into a dimension that will be easy to handle and still cover all three of the fields (e.g., 12″ x 12″). Twelve acrylic plates should be adequate.

tenance has been performed. This procedure should be performed in addition to the compliance testing that is required.

INSTALLATION/PM CHECKLIST

The Tube Support

1. Inspect wiring and electrical connections.
2. Inspect tube support movement.
3. Check that the locks are adjusted properly.
4. Inspect the counterweight assembly.
5. Inspect the tube and collimator mounts.
6. Check the tube alignment to the receptors.
7. Check lamps and indicators.
8. Check the SID indicator accuracy.
9. Check that covers are in place and securely fastened.

The Table

1. Inspect the tabletop movement.
2. Inspect the vertical drive.
3. Inspect the operation of the locks.
4. Inspect the receptor tray.
5. Check safety interlocks.
6. Check lamps and indicators.

The Wall Receptor

1. Inspect vertical movement.
2. Check the lock adjustments.
3. Inspect the counterweight assembly.
4. Inspect the image receptor assembly.

The Generator/Control

1. Check that all electrical connections are secure.
2. Inspect indicators and lamps.
3. Check that all modes of operation are functioning.
4. Inspect control panel switches, buttons, and knobs.

The High Voltage Transformer Unit

1. Inspect the high voltage cables and connections.
2. Check all the generator interface connections.
3. Check the oil level in transformer.
4. Check that covers are in place and fastened securely.

The X-ray Tube

1. Check that the high voltage cable ends are clean, sufficiently greased, and are securely tightened.
2. Check the rotor bearings (sound and speed).
3. Check x-ray calibration (noninvasively). Record the calibration results on a calibration form.
4. Take a test image to check system resolution and to check for image artifacts.
5. Check the focal spot size of the tube.

The Collimator

1. Test the field lamp operation.
2. Verify the SID indicator accuracy.
3. Check the light/x-ray field accuracy.
4. Check the field size indicators.
5. Check the operation of the AEC.

The AEC

1. Test AEC operation with a flat field phantom.
2. Check for the proper exposure index (CR and DR).
3. Test for exposure repeatability.
4. Test back-up timer function.

Finally, the service engineer should inspect all equipment surfaces for marks, dents, or scratches that could have been caused during the installation. If necessary, the engineer should touch up any surface defects. All surfaces should be cleaned thoroughly to remove grease and fingerprints. The installer should spend some time on cleaning the equipment so that it really shines. Since the customer has most likely paid a lot of money for the new x-ray equipment, it should be in showroom condition at the completion of the installation.

In addition, the service engineer should make a list of any outstanding items regarding the room that need to be addressed. These items can be corrected during the follow-up phase of the installation (see below).

USER INSERVICING

With a new equipment purchase, the installer may be asked to demonstrate its use to the staff. The demonstration of equipment operation is commonly referred to as user inservicing. Inservicing of the medical staff at the facility is a very important part of the installation process. In fact, the success or failure of a newly installed room is often dependent on how comfortable the staff is with the operation the new equipment.

Many service organizations fail to realize the importance of user inservicing. It is common to hear of situations where a new room was installed, but the staff was not thoroughly trained. As expected, the untrained technologists would experience problems, mostly operational, during the x-ray exams and, consequently, developed a dislike for the equipment. The staff perceived the problems as equipment-related and, thus, had a negative view of the equipment (and the equipment dealer, as well). Good training helps in this area.

User inservicing should be performed by an experienced member of the equipment dealer, usually designated as an applications specialist. A senior x-ray service engineer can perform this task if knowledgeable in radiographic examinations. The equipment dealer, together with the chief x-ray technician at the facility, should make a training schedule after the final room checkout has been completed. Training should be offered at different times on all shifts to ensure that everyone can attend a session. It helps to use an attendance log at each training session to ensure that all staff members have been trained.

Proper inservicing must always include a review of the operation manuals so that the technicians will know exactly where to look up information if they are experiencing difficulties with the equipment. The representative who is giving the inservicing should then provide a hands-on demonstration, showing the basic operation of the equipment, safe handling, and any special features that are available on the unit. Finally, the applications person should be present when the equipment is first used on actual patients to ensure that the equipment operates to the customer's satisfaction and to answer any questions when they arise.

FOLLOW-UP

After the new equipment has been in use for about a month, it is wise to schedule a follow-up visit to check that the room has been operating properly and, to see if the customer has encountered any problems with the equipment. Also, there is always a break-in period with new equipment where certain parts will loosen from use, or calibration adjustments could drift. The installer can check with the staff to see if the equipment meets their expectations. This is when the hospital staff will provide the service engineer with the list of additional items that they would like addressed. It is very important to examine this list carefully before taking any service action. Many of the items on the list may be related to one problem area, or the list could contain problems that were operator related. The list could also indicate symptoms of a serious failure with the equipment.

After the list is scrutinized, corrective action can be taken by the service engineer. As each item is resolved, it should be checked off from the list. This is done so that when the service is completed, the service engineer can demonstrate the corrective action that was taken for each point on the list.

Chapter VIII

PREVENTIVE MAINTENANCE

BACKGROUND

Equipment that is used regularly will tend to degrade in performance over the years. Mechanical parts will wear out due to friction and the performance characteristics of electronic components will change over time from being exposed to heat and current fluctuations. Eventually, certain components of the x-ray system will reach their useful performance life and cease functioning. Furthermore, as each of the components of an x-ray system slowly ages, the quality of the images that are produced will gradually begin to degrade.

Radiographic equipment has a predictable life expectancy that is determined by the equipment manufacturer and is termed "useful life." During its useful life, the equipment is expected to perform to the specifications stated in the equipment manuals. To help ensure that the equipment will maintain this optimum performance level, periodic inspections and adjustments must be performed by a trained x-ray service engineer. In fact, if every component of an x-ray system is inspected on a routine basis, the equipment will perform reliably for well beyond its predicted useful life.

The periodic inspection and adjustment of equipment is called Preventive Maintenance, or PM, for short. A PM on a radiographic room should be performed by an x-ray service engineer at a frequency of at least once a year for most radiographic equipment (every 6 months for equipment that is used excessively). As a rule, a complete PM on a general radiographic room takes one full day (8.0 hours) for one engineer to complete.

When a radiographic room is due for a PM, the engineer will usually call to schedule a convenient time to perform the service. This fact–that a preventive maintenance is scheduled downtime–is one of the main reasons for performing a PM and must be emphasized to the customer. Scheduled downtime means that the radiologist and staff at the facility know in advance that the room will not be available for use that day so they can arrange to perform the examinations in another room or at another site. Though it is sometimes difficult to schedule this downtime, especially at a busy facility, scheduled downtime is a much better alternative than the emergency downtime caused by equipment failure.

When equipment fails during regular working hours, a serious and usually stressful situation results for both the radiology staff and the service engineer. In this situation, the patients waiting to be imaged at the office must be sent home, and all remaining appointments must be canceled and then rescheduled for a future time. Much time and effort goes into this rescheduling. In addition, the unscheduled downtime creates problems for both the staff, who now can't "x-ray" patients but are nonetheless being paid to do so, as well as for the patients who must rearrange their schedules and sometimes drive very long distances back to the facility. Performing a PM on a regular basis effectively reduces and often eliminates emergency downtime.

A final and equally important point regarding performing regular PMs relates to patient safety. It is inevitable that some of the mechanical parts of x-ray system will eventually loosen with use. It is not uncommon to hear of situations where a piece of hardware has fallen from the x-ray tube assembly or from the table which could have injured a patient or staff member. Invariably, these mechanical failures occur on equipment that has not been routinely inspected. For safety reasons, each mechanical device in the radiographic room must be inspected regularly. One way the engineer can put this concept into perspective is to ask the question: "Would I feel comfortable if a member of my own family were being x-rayed in this room?" The clear answer is yes, if the room has been inspected and maintained regularly.

OVERVIEW

During the PM, the service engineer will closely inspect each device in the room, checking for any hardware that has loosened over time and for parts that show signs of wear. All the equipment cables will be inspected, cleaned, and tightened to eliminate the chance of intermittent failures due to faulty connections. The gears of motor assemblies will be inspected and lubricated, and all belts and chains adjusted. All the indicator lamps and control knobs will be checked to see if operating properly and will be replaced if necessary.

The x-ray tube will be calibrated during the PM. The reason for the calibration is partly due to electrical instabilities in the x-ray generator, but mostly it is necessary because of the "filament drift" that occurs with all x-ray tubes. Each time a filament wire is heated, minute particles of tungsten become vaporized and are then deposited on the inside of the glass insert of the x-ray tube. This evaporation of the filament causes an increase in resistance of the filament wire which, in turn, lowers its heating value. During the x-ray tube calibration, the filament supply voltage will be increased to compensate for the filament loss.

The collimator will be tested during the PM, the AEC checked, and the digital panel will be calibrated. When all the adjustments are completed, the engineer must perform all compliance testing required by state and federal regulations. Since guidelines vary from state to state, the engineer must obtain the appropriate documentation for medical diagnostic x-ray equipment. This information is available through government agencies, such as the Bureau of Radiological Health (or BRH).

Finally, after all the adjustments are completed, the equipment surfaces should be cleaned. This is very important because it is the first thing that the staff notices following a PM. The fact is that the radiologist or the institution has just paid a significant sum of money for the PM and expects to see some physical indication of the work that was performed. Since they cannot see most of the adjustments and calibrations that were performed, they need some visual evidence that attention was paid to their equipment.

Before beginning the PM, the service engineer should consult the radiologist and/or chief technician to find out if he or she has been experiencing any problems with the equipment. This is done so that the engineer can concentrate on those areas and directly address problems encountered there.

Many times a device may be operating at an acceptable performance level, but the hospital staff would like it adjusted to their own preferences. Without first consulting the staff, the engineer would not normally make any adjustments to the device and, consequently, must return to address this issue. This practice wastes time for both the engineer and staff and often reflects badly on the individual service engineer.

If the service engineer encounters any damaged or faulty devices, he or she should assess the situation and decide whether to repair the device at that time or perform the repair later. If a replacement part must be ordered, the engineer will, of course, return later with the new part and perform the repair. Minor repairs, those taking less than an hour, should be performed during the PM.

Many service engineers feel that since so many other duties must be performed during the PM, it is best to make notes of the repairs that are needed and schedule another day in the room for these repairs. This approach is fine if the staff at the facility is willing to cooperate. In addition, the engineer should always get the approval of the customer before ordering any expensive parts.

The PM checklist is the same one that was used for the final room checkout at the end of the installation chapter. For convenience, it is reproduced at the end of this chapter.

PM PROCEDURE

Mechanical Inspection

It is best to have an orderly routine when performing the PM. A good PM routine should start with the cleaning and inspection of all the mechanical assemblies and all the electric connections in the radiographic room. This includes the tightening or replacement of any hardware that has loosened or is missing, as well as the removal of dirt, dust, and other foreign materials from the mechanical assemblies. All bearing and bearing tracks should also be cleaned and lubricated now.

The service engineer should inspect and test all switches, locks, solenoids, and relay contacts, and correct any problems that he or she encounters. All the connections on the x-ray generator should be inspected and tightened since a loose connection could cause intermittent problems, and can affect the calibrations. Next, the belts and/or chains in the motor drive assemblies should be inspected and adjusted, if necessary. The counterbalancing systems and motor assemblies should be checked and lubricated at this time.

Mechanical inspections are always performed first for several reasons. First, it is important to have good, clean connections before attempting any adjustments. Many times a loose connection will affect the reliability of the adjustment and could also cause intermittent failures. If the engineer notices an intermittent problem during the calibration and adjustment phase, he or she will then have to stop the procedure to find the bad connection. This results in wasted time because once the problem is corrected, the engineer must completely redo the calibration.

Another reason for performing mechanical checks first is to ensure that all gears, railings, tracks, and bearings are sufficiently tightened before the alignment checks are made. As described in the last chapter, bearing adjustments will affect the alignment of the devices.

Also, a lot of dust is created when the ceiling rails and upper sections of the tube support are cleaned. These overhead areas cannot be reached without a ladder and, consequently, only get cleaned and inspected by the service engineer. The tube support should be inspected first so that the dust, can settle down before cleaning any other equipment. A dust mask (or surgical mask) should be worn during the cleaning phase if the dust is excessive.

Once the mechanical and electrical connections of the tube support have been inspected and adjusted, the engineer can perform similar checks on the radiographic table and wall receptor. When inspecting the table, the engineer should be sure to check the safety interlock switches that may have become loosened or damaged since the last PM was performed.

High Voltage Cable Maintenance

The service engineer should carefully examine the high voltage cables to see if there are any visible cuts in the rubber insulating cover. Also, the cable ends should be cleaned (always discharge first) and the individual pins of the federal connector should be spread apart if needed. Pin spreaders are available from some equipment manufacturers, but a pocket knife can be used as well.

In either case, caution must be exercised when spreading the pins because they are fragile and can easily break off. Since high voltage cables are no longer repaired in the field, a cable with a damaged pin will have to be replaced. This mistake will result in an unexpected cost to the customer (high voltage cables are very expensive). In addition, the room could be down for several days while two engineers perform the difficult task of pulling the high voltage cable through conduit that is now filled with many other cables.

To eliminate the problem of maintaining good pin contact in the high voltage well, some x-ray tube manufacturers are using a newly-designed receptacle that contains a spring in each of the pin sockets of the x-ray tube. This design ensures good pin contact and eliminates the need to spread the pins of the high voltage cable. In addition, a few cable manufacturers are now selling high voltage cables that have replaceable pins. This new design eliminates the aggravation caused by broken pins.

When the cables have been inspected and cleaned, new vapor proofing compound must be applied to the federal connectors that are inserted in the x-ray tube. Vapor proofing compound, also known as dielectric compound, is used to insulate the individual pins of the connector from ground.

When properly applied, the vapor proofing compound will surround the connector when it is plugged into the tube well. The compound forces the air (a good conductor for high voltage) out of the well, thus eliminating any chance of arcing.

The compound should be applied with an applicator (e.g., wood tongue depressor) to the end of each federal connector. This is done to eliminate any contamination (i.e., salt or oils) that could be introduced from the hands of the service engineer. Nitrile gloves, available at most medical facilities, can be worn while applying the compound to ensure that no foreign materials are introduced to the cable ends.

Enough compound should be used to form a mound on the end that completely covers the pins (Figure 37). The compound should then be applied evenly to one-half of the phenolic insulator portion of the federal connector. After the tube wells have been thoroughly cleaned, the cable end can be inserted into the well by aligning the

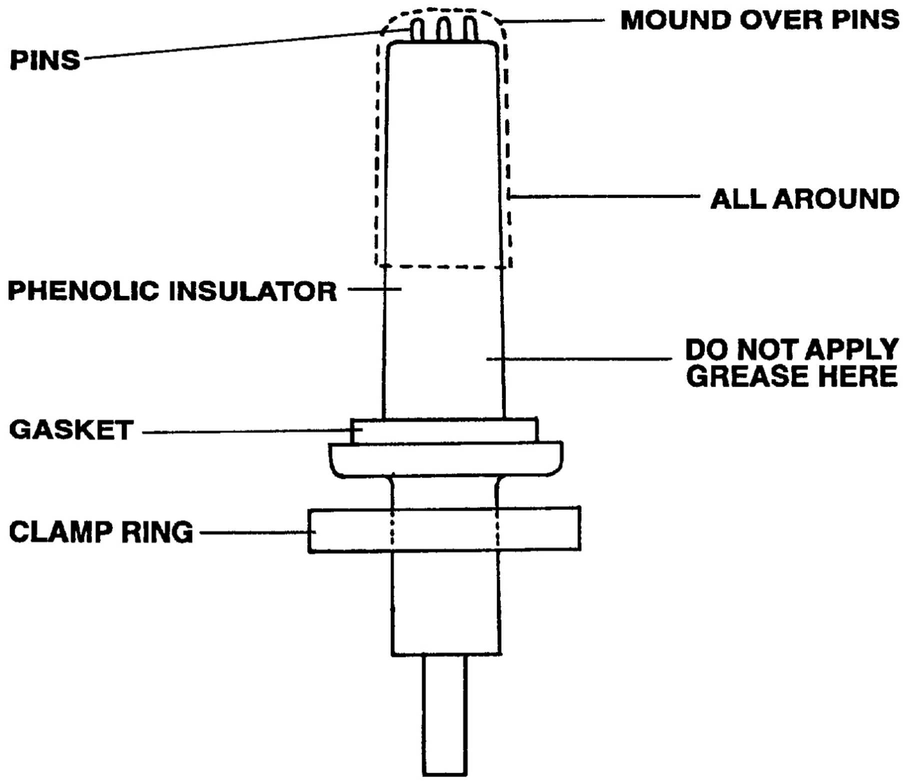

Figure 37. Application of vapor proofing compound. Correct application of the compound assures that air gaps will not form in the x-ray tube receptacle.

"key" of the cable with the "slot" in the tube well, and then pressed firmly into place.[11]

The retaining ring nut should be threaded on until the rubber O-ring is tightly compressed. The rubber O-ring acts like a protective seal that keeps moisture out of the tube well and, in addition, helps prevent the grease from drying out. If Allen screws are provided on the retaining nut, these are tightened at this time. After the vapor proofing compound has been warmed during the x-ray tube calibration, the rings should be retightened a final time to ensure that it is completely seated and all the air is removed from the well. The engi-

11. The engineer should check that the grounding ring is in place. The grounding ring is the circular metal washer that is slightly bent to act like a spring. This ring must be installed to ensure grounding integrity and thus avoid high voltage problems.

neer should perform the same maintenance on the federal connectors at the high voltage transformer. Dielectric compound, however, should not be used in the high voltage transformer wells. Instead, transformer oil is used because it is a much better insulator than the dielectric compound and does not degrade as quickly. The wells in the transformer should be filled to a depth of approximately 1/2. When the cable is plugged in, a small amount of oil should ooze out, confirming that the cable is sufficiently insulated.

Ideally, transformer oil would be used in the wells of the x-ray tube because it is a better insulator. However, since the oil could leak out whenever the tube was rotated from the upright position, a dielectric compound is used, which is more viscous. Although the vapor-proofing compound successfully addresses the leakage problem, it is only a mediocre substitute for the oil.

Vapor-proofing compound will break down chemically and will dry out when exposed to heat. As the compound dries, air gaps will form in the high voltage well providing a path for arcing. It, therefore, must be replaced, without fail, on every PM. Transformer oil does not have to be replaced nearly as often, but should nonetheless be inspected periodically.[12]

Some manufacturers of high voltage cables provide a molded rubber insulating disc that fits directly onto the cable ends. The advantage to using the disc is that it eliminates the need for vapor-proofing compound. Instead, the discs are lightly coated with a small amount of silicone oil and placed on the end of the high voltage cables. The cables are inserted in the wells and are tightened to compress the disc.

The discs are a good alternative to the grease and less messy. However, each disc can only be used one time. If a cable is removed from the well, for any reason, a new disc must be installed. The reason for replacing the disc relates to the fact that the disc becomes permanently distorted when compressed and will not seat properly if used a second time.

When the service engineer has completed the mechanical and electrical inspections, the system can be powered-up so that the lamps and switches can be checked. In addition, all other generator functions

12. Transformer oil is much more durable than the dielectric grease but will break down over time with exposure to heat. When the oil degrades, it will become discolored, changing from a clear off-white color to a dark yellow-orange. The oil should be changed when the discoloration is apparent.

such as tube safety circuits and memory function can also be tested at this time.

This is a convenient stopping point in the PM procedure to take a break. With all the mechanical inspections performed, the PM is halfway completed. The second part of the PM will proceed first with the calibration adjustments, then followed by alignment checks, image quality checks, repairs, compliance testing, and finally, equipment cleaning.

Calibration and Testing

The second half of the PM should begin with the calibration of the x-ray tube. For this calibration, the service engineer can use a noninvasive kVp meter for kVp measurements and a digital mAs meter for invasive mA/mAs measurements. If the generator provides actual kVp and mA feedback test points, they can be used since their accuracy should have been verified at installation.

The x-ray tube should be warmed-up before proceeding with the calibration by using the procedure outlined in Chapter VII (see tube warm-up). The calibration should begin on the large focus first, followed by the small focus. This is the accepted sequence used for calibration since the small filament is much more fragile than the large filament and is more easily damaged. Hitting the small filament of a cold x-ray tube, with even a moderate exposure technique, could stress the filament enough to cause permanent damage. The large filament is more durable and is always calibrated first.

Care should be taken so as not to overheat the x-ray tube. If a 15 to 20 second interval between exposures is used, the tube should remain relatively cool and should never approach its maximum heat capacity. Even so, the tube housing should be periodically checked (by touch) during the calibration to make certain that it is not overheating. If the tube feels hot to the touch, the calibration should cease for 15 minutes to a half hour. As explained in the troubleshooting discussion in Chapter IX, heat contributes to a majority of x-ray tube failures.

During the calibration, the engineer should listen to the rotor bearings and note any excessive noise. The boost/run time was setup at installation and should be correct, but it must be checked by either measuring the boost time and comparing it with the equipment manufacturer's specifications, or the actual rotation should be checked with a vibrating reed tachometer. Usually the engineer will notice obvious sound changes between successive boosts that would indicate an incorrect adjustment. When the calibration is completed, the calibration results should be recorded and checked to see that they fall within the manufacturer's guidelines. Any values that are out of range must be recalibrated.

Following the x-ray tube calibration, the collimator should be tested. The engineer should follow the collimator checklist found in Chapter VII. The x-ray tube/receptor alignment should be checked at this time, and the centering switches adjusted if necessary.

The AEC should be checked for accuracy and repeatability. However, if the customer is happy with the current image densities, it is not advisable to make any changes. Whenever a conscientious service engineer decides, with perfectly good intentions, to finetune an AEC system that is already performing satisfactorily, he or she will invariably have to return the next day to "change it back to the way it was before." Next, the digital panel should be calibrated. As noted, the panel image quality will degrade over time and must be calibrated periodically–at least once per year, minimum–to maintain the best image quality for that panel.

In the last step of the PM, the service engineer will clean the equipment surfaces. Equipment cabinets, and especially the radiographic tabletop, should be free of grease, adhesive tape, and any hand prints made by the service engineer during the PM. A multipurpose cleaner can be used on most equipment surfaces to remove dirt and grease. If there are any major scratches on the equipment, they should be covered with touch-up paint if time permits. Also, the floor must be checked for dirt and any lubricants that may have spilled during the PM.

INSTALLATION/PM CHECKLIST

The Tube Support

1. Inspect wiring and electrical connections.
2. Inspect tube support movement.
3. Check that the locks are adjusted properly.

4. Inspect the counterweight assembly.
5. Inspect the tube and collimator mounts.
6. Check the tube alignment to the receptors.
7. Check lamps and indicators.
8. Check the SID indicator accuracy.
9. Check that covers are in-place and securely fastened.

The Table

1. Inspect the tabletop movement.
2. Inspect the vertical drive.
3. Inspect the operation of the locks.
4. Inspect the receptor tray.
5. Check safety interlocks.
6. Check lamps and indicators.

The Wall Receptor

1. Inspect vertical movement.
2. Check the lock adjustments.
3. Inspect the counterweight assembly.
4. Inspect the image receptor assembly.

The Generator/Control

1. Check that all electrical connections are secure.
2. Inspect indicators and lamps.
3. Check that all modes of operation are functioning.
4. Inspect control panel switches, buttons, and knobs.

The High Voltage Transformer Unit

1. Inspect the high voltage cables and connections.
2. Check all the generator interface connections.
3. Check the oil level in transformer.
4. Check that covers are in place and fastened securely.

The X-ray Tube

1. Check that the high voltage cable ends are clean, sufficiently greased, and are securely tightened.

2. Check the rotor bearings (sound and speed).
3. Check x-ray calibration (noninvasively). Record the calibration results on a calibration form.
4. Take a test image to check system resolution and to check for image artifacts.
5. Check the focal spot size of the tube.

The Collimator

1. Test the field lamp operation.
2. Verify the SID indicator accuracy.
3. Check the light/x-ray field accuracy.
4. Check the field size indicators.
5. Check the operation of the AEC.

The AEC

1. Test AEC operation with a flat field phantom.
2. Check for the proper exposure index (CR and DR).
3. Test for exposure repeatability.
4. Test back-up timer function.

Chapter IX

X-RAY REPAIR: TROUBLESHOOTING AND REPAIRING RADIOGRAPHIC EQUIPMENT

OVERVIEW

When good quality radiographic equipment is properly maintained, it will provide relatively trouble-free operation for the stated useful life of the equipment.[13] Eventually, however, certain components of a radiographic system will experience failures regardless of quantity or quality of the maintenance provided. After a period of use, the mechanical parts of the x-ray equipment will begin to wear to the point where they can no longer function properly. Also, electronic components will eventually fail after being subjected to the countless heating and cooling cycles that occur with daily use.

X-ray equipment manufacturers take these factors into consideration when they establish the number of years the equipment is expected to function at an acceptable level of performance (i.e., its useful life). The predictions for useful life are based on the amount of time that the equipment will be used under normal conditions, which is directly related to the number of patients examined. When predicting equipment longevity, equipment manufacturers assume that the recommended preventive maintenance will be performed regularly on the equipment.

There is, however, a major factor that can greatly alter any predictions of equipment longevity–the human factor. Radiographic equip-

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13. The expected useful life of x-ray equipment varies among manufacturers. When properly maintained, most equipment should provide relatively trouble-free operation for 10 to 15 years. This is, of course, a broad generalization. Patient volume and must also be considered and can greatly alter any predictions of equipment life.

ment is designed to be operated in a specific manner. When properly operated, the equipment will easily reach its useful life. On the other hand, if the equipment is improperly handled, the life expectancy will rapidly decrease in an unpredictable way. Although equipment manufacturers account for some rough handling in their equipment designs, negligent use over time will result in a high rate of mechanical failures. The plain fact is that humans do not always interact well with machines and operator mishandling accounts for a significant number of repairs. Service engineers like to refer to this phenomenon as "job security."

In fact, most downtime for radiographic equipment is attributed to mechanical failures. The high occurrence of mechanical failures in radiographic equipment is directly related to the daily handling of the equipment by the x-ray technicians. Although some mechanical parts will eventually wear out with normal handling of equipment, careless handling will significantly increase the failure rate of the equipment and, thus, shorten equipment life. Because of the sensitive nature of this topic, any discussion of operator mishandling must be dealt with in a delicate fashion to prevent personal accusations from arising (see Chapter XIII). Equipment mishandling is, however, a fact of life and the service engineer should know that he or she will be performing mechanical repairs on many service calls.

This point can easily be demonstrated when one observes the condition of equipment in a large teaching hospital and compares it with the equipment installed in a smaller private office. The difference in appearance and operating condition of the equipment is striking. The radiographic equipment in the smaller office will invariably be in much better physical condition. This is true even if the equipment in the smaller office is much older, as is often the case.

The explanation for this wide discrepancy can be attributed to the fact that large hospitals have many different technicians, on several shifts, operating the equipment. In this situation, it is often difficult to monitor equipment use or to pinpoint those who are abusers. Moreover, it is often difficult to thoroughly train each individual technician on the proper use of equipment at larger medical facilities. Lack of adequate training for technicians (i.e., user inservicing) will result in the increased failure rate of equipment from misuse.

Another reason for the wide discrepancy in equipment condition may be attributed to the fact that with larger hospitals, the person or persons who own the equipment are not usually present to observe its daily use. Consequently, technicians may feel less responsible when using the equipment. In a small office, on the other hand, only one or two technicians may operate the x-ray equipment. In addition, the equipment was most likely purchased by the radiologist who owns (and operates) the office. This means that there is someone present who is concerned with how the equipment is being used. In this setting, the staff is more conscious of proper equipment handling because if it breaks, there is nowhere to pass the blame.

It could be argued that the larger hospital examines many more patients than the smaller office and this sufficiently explains the difference in condition of the equipment. The author would disagree with this argument, however. Although patient volume does indeed have a great effect of the longevity of equipment, it does not alone account for the drastic difference in the physical conditions of the equipment.

From a servicing standpoint, most failures with radiographic equipment will be mechanical in nature. As high as 60 percent of routine service calls involve repairs to items such as adjustment knobs, equipment handles, receptor trays, motor drive assemblies, pulleys, and roller bearing assemblies–items that are moved around during an examination. In addition, many failures occur in electromechanical devices such as mechanical switches, relays, and electromagnetic locks. Again, any device that has moving parts generally will have a higher potential for failure. Most of these devices will fail because of worn or damaged parts, or from missing hardware caused by routine handling.

In contrast to the high rate of mechanical failure, the frequency of electronic component failure is relatively low. The high quality solid state electronic components that are used in x-ray equipment today result in extremely reliable operation. It is not uncommon to find perfectly functioning, 20-year-old, x-ray generators that still contain their original (factory installed) circuit boards.

There are, however, other sources of electronic failures in radiographic equipment. One source of failure occurs with the equipment cables. This is true for all types of cables, including power cables, signal cables, and high voltage cables. Cable problems often result from the repeated overflexion of the cable that occurs during normal movement of the x-ray equipment during an examination. The constant stress applied to the cable will eventually causes the many strands of wires in the cable to fray and, finally, completely break apart.[14]

The cables that are most susceptible to stress are the interconnecting cables that run to the tube support, since it is routinely repositioned for each patient exam. These cables include the high voltage cables, rotor cable, collimator cables, and the cables that supply power to the electromagnetic locks. If these cables are stressed during normal tube movement, it is an indication that they were not hung correctly at the time of installation (see Chapter VII). The service engineer should, therefore, adjust these cables once the repair is completed. This will ensure that the failure will not reoccur.

Other electronic failures can occur in the primary and secondary power circuits of the x-ray generator. These failures are the most difficult for x-ray service engineers to diagnose for several reasons. First, these types of failures do not occur on a regular basis with radiographic equipment. A primary contactor, for example, might possibly fail once in the entire life of a given x-ray generator. Consequently, a service engineer may only see this type of failure a few times in his or her career. Thus, most service engineers have little experience with this type of failure. Second, because of the danger of electrical shock, the engineer must use great caution when troubleshooting the primary and secondary x-ray circuits. Oftentimes the failure can be detected only by the presence of high voltage arcing.

Because of the potential hazards involved, special troubleshooting techniques are required when servicing these circuits to ensure that the service engineer will not be exposed to high electrical potentials. He or she must pay strict attention to the in-circuit placement of test equipment in these power circuits or damage to the equipment (or harm to the engineer) could result. In addition, the differences between ground references and floating references must be identified in these circuits before the engineer can connect the test equipment to the individual components.

Another factor that makes troubleshooting the high-power circuits difficult is that many of the individual components of these circuits

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14. As a rule, every cable used in an x-ray room is made of multistranded copper. This is much preferred over the solid core cable used by electricians mainly because it is much easier to work with. Signal cables will have additional shielding provided under the rubber cover.

cannot be tested by using standard troubleshooting methods. For example, simple ohmmeter readings will not indicate whether a semiconductor in these circuits is defective. This is also true for testing the high voltage components. Many of these components will only fail under a loaded condition, when high current is flowing through the component. Consequently, the troubleshooting resources of the service engineer are severely limited in this area. To complicate matters further, the engineer should only attempt as few exposures as possible when trying to observe a high voltage failure. The reason for this is that if high voltage arcing occurs during the failure, other components in the system could be damaged. Again, the service engineer must utilize his or her ability to make quick observations to avoid causing further equipment damage.

Besides mechanical and electronic failures, another type of service call an engineer will normally encounter relates to image quality problems. Troubleshooting imaging problems is considered by many to be the most difficult, yet most interesting aspect of the x-ray service engineer's career. Imaging problems are caused by a failure somewhere in the imaging chain that results in a loss of image quality. Specifically, each device in a radiographic room has some effect on the quality of the final image. A failure in the imaging chain can be difficult to isolate without a thorough understanding of the image formation process (see Chapter V).

Another service-related problem is one that results from an error made by the technician who is operating the equipment. "Operator error" occurs when the x-ray technician is unfamiliar with the correct use of the x-ray equipment. The operator may not have been properly trained at the time the unit was installed, or it could be a matter of a new employee who never had the time to read the lengthy operator manuals.

Regardless of the cause, operator error accounts for many service calls. This type of service call can reflect badly on the service engineer (and the equipment manufacturer) and should therefore be corrected as soon as possible. With service calls caused by operator error, the staff at the hospital will usually forget the actual cause of the service call and, consequently, note only that the equipment is always down and the service engineer is regularly at the site. Operator error is, however, easily identified and the engineer will usually have the x-ray room up and running within a few minutes.

For review, the four most common types of service calls related to radiographic equipment are listed below in order of frequency of occurrence:

1. Mechanical failures caused by equipment handling (and mishandling), worn parts, or missing hardware.
2. Electronic failures resulting from components being subjected to heat or power surges, and from repeated cable stress.
3. Image quality problems caused by some failure in the imaging chain.
4. Operator error because of improper inservicing of the staff or the addition of new personnel who are unfamiliar with the equipment.

Most basic mechanical repairs can usually be performed by entry level service engineers (level I). However, intermediate level engineers (level II) are needed to troubleshoot and repair most electronic problems. Level II engineers can also resolve some minor imaging problems. The most difficult imaging problems and electronic failures can best be handled by senior level engineers (level III).

This chapter will cover different troubleshooting techniques that have proven successful for the author and the many well-respected colleagues that he has worked with over the past 30 years. The troubleshooting techniques outlined in this chapter will aid the service engineer in the diagnoses of common x-ray failures.

Proper Documentation

The experienced service engineer can usually isolate most failures in an x-ray system without referring to the service documentation simply because all x-ray systems are very similar in their design. However, once the problem has been isolated to a specific area in the system, the engineer should refer to the equipment service manual that was supplied by the equipment manufacturer. The service manual is needed to diagnose and test the circuits of that specific unit. Although all brands of x-ray equipment contain circuits that perform similar tasks, the operation of these circuits varies greatly among manufacturers. A good service manual, complete with schematics, a theory of operation, and a complete parts list, is a valuable tool necessary for troubleshooting radiographic equipment.

When to Call for Help

When a service person arrives onsite to repair an x-ray system that has failed in some way, the obvious goal is to get the customer operational as quickly as possible. If the engineer follows the troubleshooting sequences described in this chapter, the cause of the failure will be identified within a relatively short period, less than one hour, for example. The engineer can then decide to attempt a repair while still onsite or he or she may have to order parts and return later to complete the repair.

If, however, two hours have passed and the service engineer still has not a clue as to the cause, or even the area of the failure, then it is probably time to call for assistance. Many times, phone assistance from a colleague is all that is needed to get the onsite engineer pointed in the right direction. In addition, the engineer should seek technical support from the equipment manufacturer when unsure of equipment operation. No one expects a service person to know the design of every x-ray system in operation–there are just too many systems out there. If phone support does not help to resolve the problem, then a second service engineer with a fresh approach to the problem should be dispatched to the site to help diagnose the problem.

It is often difficult for an engineer to admit that he or she is unable to resolve an x-ray problem, especially in situations where egos are involved. Everyone likes to think that he or she is infallible and can solve any problem encountered. This is a foolish attitude that will only cause problems for the customer, as well as the service organization. No one can fix every x-ray problem that may arise. In fact, a second opinion often results in a much shorter service call. Being able to call for help without hesitation or reservation, and knowing the right time to call for help are qualities that any respected x-ray service engineer must have.

GENERAL TROUBLESHOOTING TECHNIQUES

It is difficult to teach the student troubleshooting skills in a classroom setting. Many of these skills are acquired on the job while working on equipment. Clearly, nothing can replace actual experience as the best teacher of troubleshooting equipment problems. The goal here is to provide a general method for troubleshooting common x-ray failures. Following this method, a service engineer should be able to resolve most x-ray problems. Each individual service engineer may have his or her own method of successfully attacking a service problem, and that method may vary from the procedures given below. This is totally acceptable. There really is not one approach to troubleshooting and repairing equipment.

The first task of the service engineer, when he or she arrives at the site, is to find out what exactly happened before the equipment failure occurred. When enough information regarding the failure is obtained, the engineer must then try to observe the failure and reproduce it, if possible. This step is most difficult when intermittent failures occur. Once the failure can be reproduced, the engineer will then isolate the area of the failure through a specific sequence of actions. The troubleshooting sequence must be performed in a timely manner so that any repairs can begin as early into the service call as possible. Once the repairs are completed, the system must be fully tested to ensure that the failure has been corrected.

Gathering Information on the Failure

The service engineer must first gain information as to when and how the failure occurred. Like any investigator, he or she must gather information regarding the incident (i.e., the failure) from the witnesses who were present at the time the mishap occurred. Was the equipment operating properly in days prior to the failure? At what time of day did the failure occur? Was the equipment cold or had it been powered on for a while? In what mode of operation was the machine being used at the time of the failure? In what positions were the table, tube support, and x-ray tube when the failure occurred? Did the failure occur with just one operator or did several technologists observe the same failure? Did any unusual sounds or odors accompany the failure? These are just some of the important questions that the service engineer should ask when he or she arrives at the site.

Also, the engineer should find out when the unit was last serviced and what most recent repair was made on the unit. Was preventive maintenance performed recently on this unit? Was there a recent service call for a similar problem? Were any potential problems noted on the last service call for this equipment? Oftentimes the answers to these questions will give important insight into the current problem. In fact, the current failure may be related to a recent service call. For these reasons the service professional should always inquire about the service history of the x-ray unit as part of the normal routine when diagnosing problems.

While the service engineer is gathering information about the failure, he or she should be aware that the person providing the description is recalling from memory and, consequently, may leave out (or add) important details. The x-ray technologist was most likely attending to the patient's needs and not focusing on the equipment. In addition, most x-ray "techs" who perform the examinations do not have an in-depth, technical understanding of how the radiographic system operates. The service engineer must decide whether the information can be relied upon.

It is common to hear of situations where the engineer was led in the wrong direction because the technician did not give an accurate account of the failure. For this reason, the service engineer should try to identify a person who is reliable at describing technical details and should ask that person to relate the details of the failure. Or, he or she should to try to get several accounts from different staff members at the facility. Once the information about the failure is known, only then can the service engineer begin work.

Observing the Failure

The next task in the troubleshooting process is for the engineer to try to observe and reproduce the problem that the customer is experiencing with the equipment, noting the sequence of events that led to it. If a component is obviously damaged or not working, the engineer would naturally begin the repair or replacement of the faulty component. With intermittent failures, those failures that do not occur with every use, the engineer will have to take some additional steps to try to reproduce the original failure.

The most important thing to remember when attempting to reproduce an intermittent failure is not to alter anything in the room until the failure can be observed. Frequently, a service engineer will walk into an x-ray room and immediately begin manipulating a suspected cable or connector, or changing a part that, from experience, he or she feels could be the cause of the problem. This is the wrong thing to do. If the problem cannot be observed while the engineer is onsite, it could be concluded that the problem was fixed. But in fact, there is no way of knowing if the actions taken by the engineer have indeed "fixed" the problem. Service engineers who use this unreliable troubleshooting technique could very well end up on a return service call (or service recall) for the same problem. The best approach always is to reproduce the problem, find its cause, repair the faulty component, then test the x-ray system to conclude that the repair fixed the problem.

With any failure, especially if intermittent, the best method is to let the x-ray technician demonstrate the failure to the service engineer. By doing so, the service person can see whether the operator is doing something incorrectly to cause the failure or if the equipment is malfunctioning. This troubleshooting technique will greatly aid the engineer in diagnosing x-ray failures. Once the failure can be reproduced, a major part of the troubleshooting phase is over. The service engineer can then perform the necessary steps needed to isolate the cause of the problem and then begin to take correct action.

It should be stated here that any time x-ray equipment breaks down it is a serious problem that directly affects many people. The patients who had appointments for that day must be called and rescheduled for another time. Those patients who have already arrived at the medical facility must be sent home, which often creates problems, especially if they have taken time from work, or made special arrangements for transportation. In addition, when the x-ray unit is "down," the radiologist not only experiences a significant loss in revenue since he or she cannot examine patients, but also must pay the salaries of staff members even though they are not actually working. Everyone must simply wait for the service engineer to arrive. This frustrating situation is especially devastating to a medical facility that has only one x-ray room on which to rely.

Because of the serious nature of x-ray equipment failures, the service engineer should be methodical and careful when evaluating equipment failures. On the occasions when the service engineer cannot observe the equipment failure, he or she then must regretfully inform the radiologist that the problem could not be reproduced and, therefore, no corrective action was taken, and that the failure most likely will occur again. No one wants to hear this response–not from your auto mechanic–not from your x-ray service engineer.

Finding the Highly Intermittent Failure

Sometimes the equipment will operate perfectly and not reveal any symptoms of the failure that the staff had observed. Here, the engineer should take additional steps to find the failure. If the equipment is functioning properly upon his or her arrival at the site, the service engineer should begin troubleshooting by utilizing the information concerning the failure given by the staff and focus on the most likely causes based on his or her experience.

The engineer should check for the most common causes of intermittent problems. These may include loose connections, worn cable coverings, frayed wires, discolored components, or excessive heat on individual components. If no obvious signs are found, the service engineer should begin gently pulling on those cables in the suspected areas to see if the failure can be re-created. Intermittent cable connections are a likely cause of intermittent failures. If there is an intermittent connection involved, moving the cables around will exaggerate the connection problem and, therefore, cause the failure to occur. For example, when the equipment is working, the engineer flexes or repositions one cable and the failure occurs. In this case he or she may have found the problem. Moving the cable back to its original position, if the equipment starts working, then the engineer has confirmed the failing component.

If all the cables check out ok, the engineer must then consider if the intermittent failure is occurring on a circuit board. When probing around circuit boards, components should be examined for damage and solder joints should also be visually inspected for sound connections. In addition, the individual components can be gently moved to find a poor connection that would not normally be seen. It is often helpful to use a magnifying glass when examining connections on circuit boards.

If the cause of the failure is not yet apparent, the engineer should note if the failure is related to heat, or cold temperatures. If the failure occurred after the unit had been operating for a period, the failure could be heat-related and troubleshooting should, therefore, be performed when the unit has reached normal operating temperature.

Figure 38. Block diagram of typical x-ray circuit.

When the likely causes have been checked and the intermittent failure has not yet been observed, it is time for a different course of action. At this point the engineer must change a component in the circuit that is suspected as causing the failure. The idea is that by replacing a component in the suspect circuitry, we have eliminated that one component as the cause of the failure. If the problem returns and the engineer is called back to the site, he or she can troubleshoot further knowing one component has been ruled out.

The service engineer takes an educated guess at which component could likely be the cause, replaces it, and hopes for the best. By making a distinct change in the circuit, two important goals are accomplished. First, the engineer, by pure luck, may have fixed the problem–the intermittent failure never occurring again. This often happens and is why, although a last resort, this troubleshooting technique is very useful. Second, if the failure reoccurs, the service engineer has eliminated one likely component and can troubleshoot with slightly better odds. However, when an engineer gets to the point of "blindly" replacing every component in the circuit in hopes to resolve the problem, the repair will become unjustifiably expensive. This desperate troubleshooting technique, called shotgunning, should not be used.

Isolating the Cause of the Failure

System Interlocks

When the service engineer can reproduce the failure, the next step in troubleshooting is to isolate the actual problem area. This is usually done by dividing the circuit in question into two distinct sections or "blocks" and then isolating the failure to one of the blocks. Figure 38 shows a typical block diagram of an x-ray circuit.

With most electronic devices, a command is sent from the control section of the device which, in turn, causes a specific action to occur. The control signal can be a simple command sent from a switch or relay, or a more elaborate series of commands sent from a microprocessor board. For example, on tilting radiographic tables, the tilt motor must receive a drive command before the motor will begin tilting the table. In another example, the x-ray generator must receive a command from the exposure control circuitry before the exposure will be initiated.

Figure 38 also shows a system interlock block located midway between the control block and the action block. As a rule, most x-ray circuits utilize safety interlocks to ensure that the device will be operated without risk of danger to the equipment, the patient, or the staff. The safety interlock may be found in the control logic, or it could be found in the device itself. X-ray tubes utilize thermal interlocks, for example, that will inhibit an exposure if the temperature of the tube housing becomes excessive. In addition, rotor interlocks, present in all rotor controllers, will block the exposure if the anode is not rotating. The x-ray generator has exposure interlocks that will not allow an exposure to occur if certain conditions are not met: such as whether the door of the radiographic room is closed; whether the image receptor is present; or if the tube is positioned correctly. Finally, motor driven x-ray tables have safety interlocks such as collision sensors that will not allow the motor to drive if something is in the path of the table.

In basic designs, most safety interlocks consist of a set of relay contacts that are wired in series with the control signal path so that if a safety condition is not met, the command signal path will open and, as a result, there will be no possibility of the signal reaching the intended device. Since the interlocks effectively disable key functions in radiographic equipment, this is an obvious place to begin troubleshooting. On a service call, the service engineer should first check that all safety interlocks are functioning correctly and are not, in fact, causing the failure.

If the interlock is not activated, the engineer must decide if the failure is caused by a problem in the control circuitry or by a problem in the action circuits. In the words of many experienced service engineers, "Is the device being told to operate or not?" To do this, the engineer should initiate a specific command and then check to see if that command is reaching the appropriate device. In the case of the tilting table, a good approach for the service engineer would be to activate the tilt switch while monitoring the voltage at the tilt motor and note if the command is getting there. With this approach, the area of the failure can be isolated within a few minutes.

If the signal is, in fact, present at the motor connections, then a major part of that circuit has been eliminated and the engineer can begin testing the motor drive circuits. If, however, the voltage was not present at the motor, the engineer must then find the point in the control signal path where the signal is being interrupted. In this case, several approaches to troubleshooting work equally well. The service engineer can begin measuring at the source of the control signal (i.e., where the command signal originated) and then sequentially follow the signal path until the signal is lost.

Another approach utilizes the divide and conquer tactic. With this approach, a test point midway in the circuit between the motor and the source is checked to see if the signal is present there. If present, one-half of the circuit has been quickly eliminated. The next step is to find a halfway point between the new test point and the motor. This process continues until the faulty component is found. Again, either of these approaches works well and generally takes about the same amount of time.

Exposure Circuits

The above troubleshooting procedure is rather straightforward and can be used for most simple action devices found in a radiographic room, such as with motors or electromagnetic locks. The x-ray generator, however, is more complicated in design and requires multiple input signals before it will respond with the proper action: the production of x-ray radiation. To produce x-ray radiation, a filament voltage must be applied to the tube, the correct primary voltage must be present, and all the safety interlocks of the generator must be satisfied. These conditions must be satisfied before an exposure command will be released from the exposure control logic. Once the exposure logic is satisfied, an exposure command is sent to the timer control circuitry which, in turn, signals the start of the exposure.

If the x-ray generator utilizes digital control, the inputs to the exposure control logic must be checked to see if they are present. The service engineer should check to see if the exposure logic is outputting the correct signal to initiate the exposure. Troubleshooting these complex circuits requires an in-depth knowledge of x-ray generators and is, therefore, usually performed with the help of an experienced service engineer.

There are other instances of equipment failure in a radiographic room that require an experienced engineer. For example, there are times when several failures will simultaneously occur in different circuits, producing one symptom. With this type of multiple failure, one cause that is contributing to the failure may not reveal itself until the other failure has first been corrected. In effect, one failure "masks" the second failure. Troubleshooting and isolating this type of compound failure is understandably more difficult for the service engineer. Although multiple failures are very time consuming, the engineer feels a great deal of satisfaction when he or she can solve these more complex x-ray problems.

Verifying the Cause of the Failure

When the device or component suspected of causing the failure has been found, an important task must first be performed before the engineer can begin making any repairs. He or she must first confirm that the particular component is, in fact, the absolute cause of the failure. There should not be any doubt, whatsoever, in the service engineer's mind that the repairing (or replacing) of that particular component will, in fact, completely resolve the problem.

To achieve this high level of confidence, the engineer must try to simulate the function of the component suspected of causing the failure by using a few common electronic troubleshooting tricks. Here, the engineer will electronically mimic the exact function of the faulty component using these troubleshooting tricks to see if the circuit will function properly. If normal operation returns to the circuit, the engineer can be confident that the suspected component is bad. This troubleshooting technique works well for most active components such as switches, relays, transistors, and logic gates. One trick commonly used in electronics is to use a jumper wire (with clip leads) to bypass the suspected component completely. By placing the jumper wire across the connections of the faulty component (i.e., in parallel), the engineer is "fooling" the circuit so that the component appears to be outputting the desired signal. This technique works well for switches, relay contacts, and any interlocks that are in question. If the device begins to function properly with the jumper in place, the faulty component is confirmed, with a high degree of confidence, as bad.

As demonstrated above, a simple jumper wire can be valuable (and inexpensive) troubleshooting tool for the service engineer. Another trick used by experienced engineers is to artificially inject the correct signal at the input or output of the suspected component. This technique makes the suspected component appear to be functioning so that the rest of the circuit can be tested. Service engineers successfully use this troubleshooting technique when testing digital logic circuits.

The true test that confirms that the cause of the failure has been found is when the service engineer replaces the component. With the new component in place, the engineer should observe a clear change in the operation of the circuit. If the circuit behaves in a similar manner with the new component installed, this indicates that the wrong component was replaced and the engineer should continue troubleshooting that circuit. The engineer should always observe the operation of the circuit before and after the repair to confirm that he or she has successfully diagnosed the problem.

Performing Repairs

When the failure has been correctly identified and the replacement parts are in hand, the engineer can begin to repair the equipment. As a rule, the repair should be the easiest part of the service call. An engineer possessing good electronic skills, good mechanical ability, and plain common sense should be able to perform most repairs. After the work is completed, further testing will confirm that the repair was performed properly.

Field Modifications

There are occasions when a service engineer must modify a circuit during a repair to get the device operational. A field modification is a physical alteration of the original circuit that is performed on site.

Generally, the engineer might be required to modify a circuit if he or she cannot obtain the part(s) needed to repair the device. The engineer may also decide to modify a circuit that he or she decides is not needed for the intended use of the x-ray room, or may disable a circuit that is not used by the customer. In addition, if the cost of a replacement part is exorbitant, the radiologist may decide not to have the device repaired and will simply not use a specific x-ray function anymore. In this case, the engineer will be asked to entirely bypass the circuit in question.

Consequently, service engineers will perform field modifications on occasion. There is one caveat that should be mentioned regarding equipment modifications. For many important reasons, most manufacturers of radiographic equipment must be notified before any alterations can be performed on their equipment. As a rule, any unapproved field modifications performed on new equipment will immediately void the manufacturer's warranty on that equipment. The service engineer must be aware of the consequences that could result from a field modification. Once the engineer has received written approval for a field modification (for new equipment) or has decided that a modification can be performed without a reduction in performance or safety, he or she can then perform the modification.

When the modification is complete, the engineer must make a record of exactly what was done to the device. If the engineer is modifying a circuit, he or she must document the modification in the service literature. Proper documentation includes a full description of the alteration with accompanying detailed drawings. By documenting the circuit modification, the engineer is responsibly performing his or her job. When a service engineer arrives on a future service call, he or she will be aware that the equipment has, in fact, been altered. The engineer will be able to perform troubleshooting properly since the original schematics are properly marked up showing all the changes.

Equipment Testing

When the repair has been completed, the service engineer must thoroughly test the functions of the x-ray system. Final testing should not be limited solely to the device that was repaired since most individual devices in the room are interconnected to form an x-ray system.

Testing should verify the operation of the device that was repaired, as well as the functionality of entire x-ray system. The greatest amount of service recalls result from the service engineer not thoroughly testing the system after making a repair. The reason for testing all functions of the x-ray system after a repair, including those functions that have absolutely no relation to the circuit that was repaired, is partly the result of the compact design of today's radiographic equipment. The fact that the internal components are so closely positioned to each other often makes repairs difficult to perform.

For example, a wire harness may have been moved and accidentally disconnected while the engineer was repairing another circuit located adjacent to the harness. In fact, with some repairs, a major assembly may have to be completely removed from the equipment cabinet before the failed component can be accessed. Furthermore, when working in tight spaces, the engineer could inadvertently disconnect or damage an unrelated circuit without his or her knowledge.

This information should not surprise the reader of this book. Problems caused by the engineer (i.e., "self-induced" problems) do occur in the x-ray servicing field, as is the case with all other service professions. However, if the engineer checks every function in the x-ray system before he or she leaves the site, most of these secondary problems will be discovered and immediately corrected. Although a functional checkout requires additional time to complete, it is well worth the time invested.

Troubleshooting Sequence

To recap, a troubleshooting sequence that will aid the service engineer to successfully resolve x-ray failures is as follows:

1. Gather as much information as possible about the failure.
2. Reproduce the failure.
3. Troubleshoot to isolate the faulty component.
4. Verify that the suspected component is the cause of the failure.
5. Perform the repair.
6. Check that the replacement component is functioning properly.
7. Test the entire x-ray system.

COMMON EQUIPMENT FAILURES

Radiographic equipment can fail in any number of ways. Since a major goal of this book is to prepare the student who will soon begin a career in this field, examples of common equipment failures will be described in the following pages. These failures can occur with any "brand" of radiographic equipment due to the common designs. The objective here is to provide actual examples of equipment breakdowns that the service engineer will encounter during his or her career.

Failures with the X-ray Control

The main function of the x-ray control is to regulate the production of x-ray radiation. It also monitors many other functions in a radiographic room, such as the safety interlocks, the status of the x-ray tube, and other fault conditions. It is the brain of the x-ray generator. The discussion here, however, will be limited to specific failures with the output radiation that result from a malfunction in the x-ray control.

The most devastating failure of the control is when no radiation is being produced, and so we will begin our discussion here. To produce x-ray radiation, three components are needed (assuming a functional x-ray tube): high voltage, or kVp; tube current, or mA; and an exposure start signal. If one of these signals is missing, x-ray production will not occur.

Common kVp Failures

To develop the kilovoltage, the x-ray control uses the dedicated power line supplied by the facility and converts the voltage to a level that is sent to the high voltage transformer. Single-phase x-ray generators use an autotransformer for kVp control. The autotransformer takes the incoming line voltage supplied by the power company and provides the multiple output voltage that are used to vary the primary voltage. The operator will select a kVp setting on the x-ray control which, in turn, activates a corresponding tap on the autotransformer which sends the appropriate primary voltage to the high voltage transformer to produce the desired kVp (Figure 4). This is the most basic example of kVp control.

As mentioned in Chapter III, a special switch, called a primary contactor, is installed in series with the primary circuit. The primary contactor closes at the start of an exposure to supply the selected primary voltage to the primary winding of the high voltage transformer. A typical contactor is made of two high power SCR's (silicone controlled rectifier). The primary contactor is switched on by an exposure start command, which originates from the operator exposure handswitch. When the x-ray technologist depresses the exposure switch, an exposure start signal is sent to the timer circuits which initiates and controls the exposure time (the time that radiation is emitted from the x-ray tube). This is time control.

Since as much as 300 amps can pass through the components of the primary circuit, it is reasonable to assume that over time they will experience failures. When a failure occurs anywhere in the primary circuit there cannot be any radiation produced. Common components that fail with single-phase units are the kVp selection tap switches, where the internal contacts become burned and pitted over time. When a kVp tap switch fails, it cannot be repaired in the field and, therefore, must be replaced. Another common component failure occurs with the primary SCR contactor. These contactors will burn out and create an open circuit (no x-rays produced) or will short causing an excessive load on the incoming line causing the incoming line breaker to trip.

With high frequency generators, the incoming line is fed to the power section of the generator where it is converted to a DC voltage, sent to the power inverter which creates the high-frequency signal that is sent to the high voltage transformer (Figure 7). Since relatively high DC voltage levels are developed and regulated here, components in the power unit, especially the capacitors, can fail. Also, the fast switching components of the inverter, IGBT's, for example, can short out. Both failures will inhibit the production of high voltage, and therefore, no radiation will be emitted.

Common MA Failures

MA is controlled by providing a highly-regulated power source to the filament transformer that is submerged in insulating oil in the high voltage transformer assembly. The power supply should remain steady throughout the ranges of selected mA's. In single-phase generators, the filament stabilizer transformer, located in the x-ray control cabinet, provides this regulated supply to the filament transformer (Figure 8). When an mA station is selected, a specific voltage is sent from the stabilizer, through the mA adjusting resistors, to the primary of the filament transformer. During the exposure, the filament secondary current will be in the range of 4.0-5.5 amps, which represents a significant load to the supply. Maintaining this regulated output puts a great demand on the stabilizer. Consequently, filament stabilizer transformers can fail over time.

High-frequency generators have much improved mA control. High frequency pulses are created on the mA control board found within the x-ray control. The pulses are sent to the filament transformer, just as with single phase generators, where it is stepped up to the correct level to drive the filaments in the x-ray tube. High-frequency drive allows for better mA control while using smaller components and less power. Failures to the mA control board can occur, although they are rare. Usually, lack of mA is a result of an open or shorted filament wire (see below).

Failures with the High Voltage Transformer Unit

The main function of the high voltage transformer unit is to "step up" the selected incoming primary voltage to a high voltage which will then be rectified (converted to DC) and applied to the x-ray tube. A second important function is to step down the selected primary filament voltage to a level that can be applied to the filaments of the x-ray tube. Thus, the major components inside the high voltage transformer unit are the high voltage (step up) transformer, the rectifier diodes used to create the DC high voltage signal, and the filament (step down) transformer.

Each of these components has the potential to fail during the life of the x-ray equipment. Shorted diodes will result in an "overload" condition, tripping the main breaker. Open rectifier diodes will result in no x-ray radiation. Because of the potentially dangerous voltages that are present in the transformer unit, the engineer is severely limited in his or her troubleshooting techniques. To complicate matters even further, the components in the transformer unit are completely submerged in insulating oil inside the sealed tank. Consequently, it is not a common practice to service the internal components of the transformer unit on a routine service call. Rather, if the rectifiers in the transformer are suspect, the entire transformer unit is replaced.

The other major component in the transformer unit that can fail is the filament transformer. A quick check is to look directly into the exit port of the x-ray tube. If the filaments are not glowing the engineer should first check that the primary filament voltage is present. Convenient test points, located on the top of the high voltage transformer unit, are provided for making these measurements: XL for large focus, XS for small focus, and XC for filament common. If the primary voltage appears correct, then the problem can be with a defective high voltage cable (very common), or the filament transformer is the culprit. High voltage cables are expensive but can be replaced. It is not common to repair internal components in the high voltage transformer tank. With a faulty filament transformer, the entire high voltage transformer unit should be replaced.

Failures with the X-ray Tube

X-ray tubes can fail in several ways. For example, the filament wires could open, the tube could experience high voltage arcing, the anode could become pitted, the radiation output could drastically fall off, the resolution of the tube could change, the housing seal or the glass insert could break causing an oil leak, or a receptacle could get damaged.

Damage Caused by Handling

Since x-ray tubes are very expensive (costing $5,000 or more), it is imperative that the service engineer exercise great care when installing or handling them. The glass insert located within the tube metal housing is very fragile. To ensure that no damage will occur, x-ray tubes should be repackaged in their original shipping carton when being transported to the site. Careless handling of a tube will usually cause the glass insert to crack which renders the tube useless. When installing a tube onto its supporting device, the engineer should make sure that the tube is safely mounted using a thread locker. Also, the engineer should carefully thread the cable nuts from the high voltage cables into the tube wells. If a cable nut is accidentally cross-threaded into the threads of the x-ray tube well, the threads could be permanently damaged.

Heat-Related Failures

If an x-ray tube is properly installed and regularly calibrated, the engineer can expect 10 or more years of tube life for general radiography. X-ray tubes last much longer and fail less often than in the past mainly because exposure times are much shorter for most examinations performed today. It is a fact that heat causes damage to x-ray tubes and taking shorter exposures results in less energy delivered to the x-ray tube, and thus, less heat. The shorter exposure times are a direct result of the quick response of digital receptors, and from the regulated outputs of high-frequency generators. Excessive heat will damage the glass insert over time and will ultimately shorten the life of the x-ray tube. For this reason, manufacturers take great measures to ensure that heat will be dissipated from the glass insert. Tube designs include larger tube housings, which are filled with more insulating oil that can dissipate the heat. Also, box fans are attached to the housings to aid in cooling.

The anode bearings of a rotating anode x-ray tube are extremely susceptible to the effects of excess heat. Over time, the heat will cause a breakdown in the lubricant of the internal rotor bearings and, as a result, the anode will begin to produce a distinct audible sound during rotation. This sound will become increasingly louder over time and, at some point the bearings will seize up and the anode will no longer rotate.

Excessive heat could also damage the tube housing. A rubber seal, called the bellows, is specifically installed in the cathode end of all x-ray tubes to allow for oil expansion caused by heat. Because of size limitations, the bellows can only compensate so much for heat expansion. Consequently, if too much heat is accumulated in the tube, the seal could burst.

Anode Failures

Since the target of the anode is constantly bombarded with high speed electrons, it will eventually begin to show signs of wear. If the x-ray tube was installed correctly, is regularly calibrated, and the operator strictly follows the daily tube warm-up procedure, the target should remain in good condition for the entire life of the tube. Problems arise only when the above criteria are not followed. If a cold target, from a tube that was idle for several hours, is hit with a high technique exposure, the thermal stress caused by the contrasting temperatures on the target surface could cause the target to become warped, and no longer useable. Thermal stress can also cause pits or cracks to form on the target surface. If the target is pitted (or cracked), erratic exposures will most often result.

Most anode problems, however, relate to the rotating anode. With these tubes, the anode must rotate at the correct speed (and direction) so that the maximum exposure ratings of the tube can safely be achieved. In fact, much higher exposure techniques can be achieved with a rotating anode versus one with a stationary anode. During an exposure, electrons impacting the anode produce a great amount of heat. Recall that 99 percent of the energy used for x-ray production is dissipated as heat. The anode is rotated specifically to dissipate the heat evenly across the entire anode surface.

If the anode fails to rotate, it will be permanently damaged. Usually, the area of impact on the target surface of a (now stationary) anode will melt and become permanently deformed. Even if the engineer repairs the anode rotation problem, the tube will be unusable. The reason being that each time the electrons impact the damaged area of the target, the resulting radiation will be unpredictable and erratic, causing inconsistent exposures.

Anode rotation failures can occur if the rotor bearings seize (from heat damage) or if there is a failure in the rotor controller. The engineer can quickly narrow down the failure by removing the end cap of the x-ray tube (anode end) and attaching the leads of an oscilloscope to the stator shift and stator common leads. An AC voltage should be present at the tube during the boost and run cycle. The boost voltage for low-speed rotation should be about 200 VAC and the run voltage should be in the 60 VAC range. In addition, the stator main and shift voltages should be out of phase when viewed on the oscilloscope. The degree of phase shift is dependent on the shift capacitor used on the rotor controller and the type of x-ray tube used.

If the voltages are correct but the anode is not rotating, then the anode bearing assembly probably has seized and, consequently, the tube must be replaced. If no AC voltages are present, or an incorrect voltage is present, the problem is with the rotor controller. Most low-speed rotor controllers are located inside the x-ray control unit. The engineer should repair or replace the rotor controller to correct this problem.

If the anode is rotating, the rotation speed (in rpm's) should be measured with a vibrating reed tachometer (see Chapter VII). At installation, the service engineer configures the rotor controller to match the specific x-ray tube. He or she will adjust the boost and run times to achieve the rotation speed. An anode that is rotating at a speed that is much slower than its rated speed will also fail prematurely. In this case, the anode will accumulate excessive heat that it will not be able to dissipate properly. Over time, the anode will become warped or pitted, causing erratic exposures, and the tube should be replaced.

Filament Failures

In addition to anode failures, the cathode of the x-ray tube will also experience a few failures. These failures will mostly occur with the filaments of the x-ray tube. A filament wire can break creating an "open circuit" or it can become "shorted" to the focusing cup. During an exposure, the filaments are heated and, in turn, will emit electrons. Along with the emission of electrons, a small amount of the tungsten material is also released in a process called filament evaporation. The evaporated tungsten will be deposited on the inside wall of the glass insert. Excessive tungsten deposits could lead to arcing within the tube insert, which is discussed later in this chapter.

Over a period of years, filament evaporation will cause the filament wires to gradually become thin and brittle. When a very brittle filament wire is subjected to a high inrush current, it will pop open. In the case of an open filament, the radiologist will usually report that he or she is not getting an exposure on either the large or small focus setting. The service engineer can easily confirm that a filament has, in fact, "opened" by removing the collimator from the x-ray tube and looking directly into the port of the x-ray tube, first with the generator powered off. It should be obvious that the filament wire is broken. This method of direct observation is the most reliable method for diagnosing an opened filament wire.

If, however, the tungsten deposits on the port of the tube are partially obstructing the view of the filaments, the engineer can measure the resistance of the wires. The resistance measurement should be made at the pins in the cathode well of the x-ray tube.[15] Again, the bad filament should be obvious, as indicated by an extremely high resistance reading. If the engineer obtains similar readings between large and small focus, the problem may be elsewhere.

The engineer can also inspect the filaments with the generator powered on. With power turned on, the engineer should alternately select between large and small focus and confirm that one filament is not lighting.

Another way the filament will fail is that it can short to the focusing cup of the cathode. With a shorted filament, the radiologist will experience a generator overload condition when attempting to make an exposure. When the generator detects an overload condition, the control circuits will automatically shut down the generator completely. The overload is a result of excessive tube current caused by the shorted filament. The shorted filament will draw excessive filament current which, in turn, creates a very large space charge that produces the high tube current. A shorted filament can be verified by looking directly into the port of the x-ray tube during standby (i.e., no radiation) and see the shorted filament sagging and touching the focusing cup of the x-ray tube. Another way to confirm a shorted filament is by making resistance measurements.

Low Radiation Output

An x-ray tube failure, although very rare, relates to the radiation output of the tube and is caused by a problem with the filament wires. The engineer will discover this failure during a routine calibration, or on a service call for a complaint of light images. Here, the desired mA cannot be achieved, regardless of the amount of filament current present. The low mA output results in a low radiation output. This rare type of failure mostly occurs with tubes that are very old, or in tubes that have been heavily used. It is rare to find this failure in a new tube.

The failure is very straightforward to diagnose. The engineer can use a radiation meter to measure the tube output. The output of the

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15. Since it is difficult to reach these connections, a test connector can be made from an old spare high voltage cable. The cable is cut six inches back from the federal connector and the three conductors should be stripped back to expose the bare wire. For testing, the engineer will insert the test connector in the well of the tube (with power turned off) now using the bare conductors of the cable for the resistance measurements.

tube, obtained at a standard technique setting and SID (as specified by the manufacturer), can be calculated as a measurement of mR/mAs. The output can be compared to the manufacturer's guidelines, or from previous readings that the engineer should have obtained during a calibration. If the output is low, the tube should be replaced.

X-ray Tube Arcing

Internal arcing is another common way in which an x-ray tube can fail. A high voltage arc can occur by two means: (1) an alternate path of conduction within the glass insert and (2) a breakdown or reduction of insulating oil within the tube housing. In either case, the arcing that occurs within the tube housing is potentially dangerous to persons who may be near the x-ray tube. Furthermore, the high voltage arcs will often cause additional damage to other circuits in the x-ray system. Usually, the arc will travel back through the system causing damage to some other component in the x-ray generator. Therefore, it is crucial to diagnose high voltage arcing failures as quickly as possible.

High voltage arcing will most often occur within the glass insert of the x-ray tube. As stated earlier in this chapter, tungsten deposits will eventually accumulate along the inside walls of the glass insert. Over time, excessive deposits will create a conductive path for the beam of electrons to follow. Since the beam of electrons normally travels through the evacuated space of the x-ray tube (which is highly resistive), a path of tungsten metal will provide a less resistive path for the electrons. The tungsten, in effect, is providing a direct short from the anode to the cathode of the x-ray tube. The short circuit will cause excessive tube current which creates on overload condition. Most tube overloads will shut down the generator completely.

Internal tube arcs are easily detected. The first obvious sign is the loud snap or pop that is heard originating from the x-ray tube. Once the engineer confirms that the sound is emanating from the tube, he or she must then determine if the arc is occurring inside the tube or at the high voltage wells. If in the high voltage wells, the engineer can remove the high voltage cables and view the arcing tracks inside the wells of the tube. In this case the engineer will thoroughly clean the wells and apply new dielectric grease to the cable ends to solve the arcing problem.

"Gassy" Tubes

Another type of failure with x-ray tubes is related to gas that develops within the glass insert. As the filament wires become vaporized over time, a small amount of gas will be released. Under normal use, this gas is absorbed into the inside surface of the glass wall of the tube insert and does not cause a problem. If, however, the tube is not used for several days, or if it has been stored on a shelf for several months, the surface of the glass may begin to release these gas molecules.

Any gas molecules in the path of the electron beam will create a conductive path that will, in effect, create an internal short within the glass insert. As with any internal arcing, the excessive current will cause the x-ray generator to shut down. With tubes that have been inactive for very short periods of time, several days to a few months, for example, this problem could be remedied by seasoning or conditioning the tube (see Chapter VII).

However, after a much longer period of inactivity, an excessive amount of gas will accumulate within the glass insert x-ray tube. In this case, tube seasoning may not correct the situation. The large number of gas molecules will not be reabsorbed into the glass surface during the tube seasoning process. At this point the tube is said to become gassy. A gassy tube must be replaced.

Failures with the High Voltage Cables

The high voltage cables connect the x-ray tube to the high voltage transformer. These cables conduct high voltage and experience unique failures. A failure with high voltage cables can cause a service engineer to completely misdiagnose a problem in a radiographic room.

The most common problem occurring with high voltage cables is that one or more of the conductors within will eventually break open. These cables are routinely flexed and twisted during each x-ray exam, and over time the constant stress will cause the wires to fray and eventually break. If the cables were properly run (coiled and hung) during the installation, they experience less stress and fewer breakdowns.

Although any interconnecting cable can experience stress and broken wires, a broken conductor in a high voltage cable will produce unusual symptoms that can confuse the service engineer when he or she is diagnosing a problem. In a low voltage signal cable, a break will represent an open circuit and the attached device will simply not function. With high voltage cables, the high voltage signal will tend to "jump" across the air gap formed by the break in the wire. A cable arc will often produce symptoms similar to an x-ray tube arc, causing the x-ray generator to shut down or it may cause an erratic kVp output. Also, the high voltage spiking will damage other sensitive components in the system such as circuit boards. If an opened conductor is confirmed as the problem, the engineer must replace the cable since they are not repaired in the field.

The conductors in the high voltage cable could also, from stress, become shorted to each other. This is not a problem for the anode cable since the three conductors are shorted together at the high voltage receptacle anyway. It is, however, a major problem for the cathode cable, which uses the three conductors for the filament circuit as well as for conducting high voltage. A shorted cathode cable will cause a filament failure which could damage the filament transformer. The cable should be replaced if a short is suspected.

Failures with the Collimator

As stated in Chapter IV, the collimator is the main safety device in a radiographic system. The main function of the collimator is to limit the size of the radiation field to a specific area of the patient's anatomy. By doing this, it greatly reduces the amount of scatter radiation which can expose the patient as well as the staff. It accomplishes this beam limitation with two pairs of mechanical shutters. The blades of the shutter assembly open and close to vary the radiation field size in the longitudinal and transverse (or cross) directions. Manual collimators are the most basic in design and generally provide trouble-free operation barring damage caused by a collision with another device in the x-ray room, which happens occasionally. If the collimator was physically damaged, its housing should be carefully inspected for dents that could create gaps in the housing. Collimators are lead-lined to provide additional shielding from off-focus radiation so the housing must be completely intact. The engineer should also check and secure the internal hardware during a PM since screws tend to loosen up with use.

Automatic and motorized collimators include the addition of a motor to drive the shutter blades into position as well as the circuitry to control the movement of the shutters. These circuits need to be adjusted periodically. However, the most common failure that occurs with automatic collimators relates to the Positive Beam Limitation (PBL) system failures. Most automatic drive failures are a result of the collimator shutters not moving to their correct position, or not moving at all, when the image receptor is in place. Shutter motors will fail, and the gears and linkage can wear over time. Often the failure with automatic collimators is due to an incorrect or missing collimator drive signal that originates at the receptor size sensing circuitry. The size sensing feedback signal is sent from the image receptor to the collimator logic to cause the shutter motors to drive.

Failures in the Lamp Circuit

By far, the most common failure occurring with collimators relates to the field lamp and lamp timer circuit. As of the writing of this third edition, most collimators still utilize a halogen lamp to achieve the light intensity required to visualize the light field. The many problems associated with the use of these high intensity lamps are described below. Fortunately, newer LED technology is gradually replacing the halogen lamp so that many of the failures related to the lamp circuit have, effectively, been eliminated.

Since the purpose of the field lamp is to visibly indicate the radiation field, the field lamp must be bright enough to be seen in normal room lighting. To achieve this brightness (minimum of 160 lux), the collimator must have a power supply capable of supplying high current, as much as 6 amps, to the halogen lamp. In addition, a lamp timer circuit is used to switch the lamp on for a set period of time (typically 30 seconds) then automatically turn the lamp off. The high current used in the lamp circuit has a two-fold effect. First, the high current introduces heat that can damage the components in the lamp circuit used for switching the lamp on. The two most common devices used for switching are relays and solid state switches, such as a Triac. When switched on, the high in-rush current can damage these components as they age. For this reason, it is common for a service engineer to replace the lamp timer board used in collimators.

In addition, because of the high inrush of current, the collimator lamp itself will burn out regularly. The filament wire in the lamp becomes brittle with regular use due to the evaporation of tungsten, which is commonly used for lamp filaments. At some point, the high inrush current will pop the filament at turn on.

Besides the effects of inrush current, the high current flowing through the lamp generates a significant amount of heat within the collimator housing. Manufacturers of collimators employ heat shields to dissipate the heat so as not to damage the collimator. The heat shields work well unless there is a failure in the lamp timer circuit that forces the lamp to remain lit indefinitely. This very common failure introduces excessive heat inside the collimator assembly that will damage (melt) other components within the housing.

Collimators are positioned for each exam throughout the day, which causes parts to loosen and wear. As a result, collimator repairs account for a significant amount of service calls. It is important to emphasize that after any repair to the collimator, the service engineer must test every function of the collimator, especially the light field to x-ray field congruency. Again, with LED technology, most of the problems related to heat have been eliminated.

Failures with the Image Receptor

The image receptors found in a radiographic room as of the time of this writing can be either film, which has been almost completely phased out, the CR cassette, which will be obsolete within a few years, or the digital flat panel, which is currently the best and most preferred receptor. CR cassettes experience the same types of problems as do film cassettes. Mostly, they are damaged by mishandling, especially when they are dropped. Once the cassette frame is bent, they develop light leaks which causes overall fogging on the image, degrading image quality. At that point they should be replaced. The intensifying screens of the cassettes must be regularly cleaned to ensure that artifact will not be present on the images. The cassettes must be tested to verify proper screen contact.

An erasure test should be performed quarterly on all CR units to ensure that the erasure lamps in the CR scanner are completely erasing the image after a scan so there will be no latent images on the image media that could be seen on subsequent exams. If not erasing completely, the erase lamps should be replaced. Also, the CR imaging plate wears over time and must be replaced when image quality degrades. Furthermore, the CR scanner optics should be calibrated routinely and when image quality degrades. As mentioned earlier, the scanner contains mechanical rollers, belts, and gears that should be regularly replaced during a preventive maintenance service call. Worn or dirty rollers cause feed problems and can create image artifacts.

Digital flat panels, when properly cared for, can provide five (or more) years of trouble-free operation. This is especially true when the panel is permanently fixed in a grid cabinet or in a table or wall Bucky. However, if the digital panel is moved around between wall and table receptor cabinets, or used in a mobile setting, it can fail in several ways.

If a tethered panel is used, the tether cable that connects the digital panel to its power supply unit will wear over time. The tether cable gets pulled on, or can get tangled in a patient's bed causing permanent damage. The connection where the tether cable attaches to the panel is another common point of failure. If the wires within this cable are damaged, the panel will not function properly and will have to be replaced.

The panel, itself, will develop problems if exposed to extreme temperature fluctuations, such as in mobile x-ray applications. Flat panels should be carefully handled at all times due to their compact design. Recall that the panels contain an array of transistors, delicate electronic sensors and circuit boards, and glass in many cases. If the panel is dropped, these components could get damaged. Many digital panels have drop sensors that record the number and intensity of impacts. This information is used by the panel manufacturer to monitor handling. Excessive impacts on a panel could void the warranty. Also, all panels have weight limit ratings that should not be exceeded. Fortunately, protective panel covers are available to reduce impacts and increase the weight rating of the panel. If a panel normally can withstand 300 pounds of force overall, adding a protective cover can increase the weight capacity to 800 pounds or more.

Wireless panels are more desirable today because they eliminate the tether cable completely, thus reducing a major component that can fail. With wireless panels, a more common problem relates to connectivity. These panels communicate with the host computer via wireless network connections, which can be problematic, at times.

The image receptor is housed in a simple grid cabinet or within a motorized Bucky assembly. Both types of receptor cabinets utilize a tray to hold the DR panel (or CR cassette) in place, which are subject to mechanical failures. If a Bucky assembly is installed, there are some electromechanical failures that will occur. The reciprocating grid assembly is usually the source of most Bucky problems. A symptom that often indicates a grid failure is a complaint of grid lines on the image. The grid lines are caused by the fact that the grid is no longer moving during the exposure. It should be recalled that a reciprocating grid has a lower grid ratio and grid frequency (Chapter V), resulting in much thicker lead strips than those of stationary grids. The thicker lead strips will be clearly visible on the image if the grid is not moving, or if moving at the incorrect speed. With a reciprocating grid failure, the grid itself could be jammed, the grid motor could have failed, or there could be a problem with the linkage between the motor and grid assembly.

Other Common Equipment Failures

During an x-ray examination in a general radiographic room, the tube support, wall receptor, and radiographic table are constantly repositioned for each patient that is examined. Because of this repeated movement, these three devices are prone to mechanical failures. Common mechanical failures occur when parts loosen due to the vibrations and shocks caused by the movement. In addition, many mechanical parts are damaged because of equipment abuse such as collisions, overtightening of locks, and other careless handling.

Besides mechanical failures, a common area of failure for tube supports and radiographic tables is with the electromagnetic locks. The electromagnetic locks on radiographic equipment will exhibit failures during the life of the equipment for three reasons. First, the power supplies for most electromagnetic locking systems are generally basic in design and cheaply manufactured. Manufacturers try to save expense in this area and will use a basic, unregulated power supply.

Another reason for the high rate of failures has to do with the fact that the electromagnetic locks in a radiographic room are usually operating in the energized state for most of the working day.[16] The locks are de-energized only when the tube, table, or wall unit is being repositioned while examining a patient. While the locks are energized and holding the device in place, electric current is flowing through the locks. This constant current heats the locks to the point that they can often be hot to the touch. This heat, applied over time, will cause damage to the coil within the lock, or the wire insulation of the lock.

The electromechanical lock works by friction. Thus, the material on the surface of the lock will slowly wear away over time. This condition is exaggerated when technicians attempt to move the device without first releasing the locks. In addition, if the locks are not aligned squarely with the locking surface, excessive wear and even damage could occur. For this reason, it is important to properly adjust all locks at installation and then check the adjustments at every PM.

Another component on a table or tubestand that commonly fails is the centering and travel limit switches, and their associated detents. Centering switches, as the name implies, are used to indicate the center alignment position in a radiographic system. The x-ray technician must be sure that the receptor is exactly centered to the x-ray tube before taking an x-ray. At the time of installation, micro-switches, and their detents, are permanently installed so that they will activate a signal when the tube is properly centered to the receptor. In addition, travel limit switches are commonly used in motorized tables, tube supports, and wall receptors. The micro-switches used in these circuits are often generic in design, utilizing lightweight actuators, and can fail over time.

16. Electromagnetic locks should not be confused with the solenoid style lock. Solenoid locks normally remain in a de-energized state and are activated only when repositioning the tube support or table.

Chapter X

THE MOBILE X-RAY UNIT

The mobile x-ray unit, also referred to as a "portable unit," plays an essential role in radiography.[17] With mobile x-ray, the x-ray system is transported to the patient for the examination, providing a vital service to patients considered non-ambulatory, those people who are not able to move about on their own. Mobile x-ray units are used daily within hospitals for patients who, due to critical illness, cannot be transported to the radiology department. Patients under critical care, for example, who are confined to areas such as the intensive care unit (ICU) or in the emergency room (ER) require mobile x-ray services.

Furthermore, mobile x-ray units allow healthcare service providers to perform x-ray examinations remotely on patients who, due to age or illness, cannot travel to a hospital. Elderly people living in nursing homes, or those who have disabilities regularly require mobile x-ray services. It is a fact that as the population ages, mobile x-ray services will play a key role in the delivery of healthcare to the public. Originally designed in 1919, the mobile x-ray unit became popular after it was used successfully during the Second World War in field hospitals. Today, it remains a valuable tool for x-ray imaging.

The mobile x-ray unit is a complete x-ray system on wheels. The x-ray control, x-ray generator, x-ray tube, collimator, tube support, and a storage bin for the image receptor are mounted directly onto a mobile cart. To be truly mobile, each of the components of the mobile x-ray system are necessarily smaller and more compact than those found in a fixed radiographic room. Historically, the challenge has

17. The term "portable," short for portable x-ray unit, originally referred to a unit that could be carried by hand. Today, most professionals in the x-ray field prefer to use this term over mobile x-ray unit. In fact, a technician taking a radiograph with a mobile unit is said to be "doing a portable."

been to find a way to develop a unit powerful enough to obtain good quality images like those from a fixed x-ray unit, yet light enough to be transported.

Mobile x-ray units come in several different designs, depending on the intended application and where they will be used. The most basic designs are extremely lightweight, are manually driven (i.e., pushed by the operator), and receive power directly from a standard wall outlet. These units are ideal for transporting to nursing homes, for example. Other designs are "self-powered" and use internal batteries to supply power to a motor drive system for transport, and to power the x-ray generator during the examination. Because battery-powered units are generally larger (and heavier), they are used mainly in hospitals. Some mobile units use a combination of both line power (for x-ray) and batteries (for transport). Regardless of the type, mobile units can produce quality x-ray images even with their compact size.

BACKGROUND

The earliest design of the mobile x-ray unit was derived from the portable x-ray unit, which was the least expensive and thus, most popular x-ray machine available to the doctors who would become the first "radiologists." Those early portable machines consisted of an x-ray generator, x-ray tube with a stationary anode, timer control switch, and fixed cone that attached to the port of the x-ray tube. These units had to be small and light enough to be carried by hand to a medical office or to the patient's home. In fact, most portable units were designed to fit inside a standard size briefcase or small suitcase. This compact design, however, limited the size of the components used to generate radiation, particularly the high voltage transformer and x-ray tube. Consequently, early portable units had a much lower radiation output as compared to the standard radiographic equipment found in a radiology department. Since they operated with conventional AC line power, these portable units required very long exposures to achieve a good image. Even so, they could produce good quality radiographs for many common exams. Handheld portable units (now with high-frequency generators) are still commonly used today in applications such as with veterinary examinations

Over time an increasing demand for remotely performed x-ray exams called for an improved portable x-ray machine. These machines had to be larger and more powerful to perform a wider range of x-ray exams, through a full range of kilovoltages, yet still be mobile. They had to provide a means to angle the x-ray tube to achieve the standard x-ray views. In response to this demand, equipment designers increased the size of the x-ray tube and generator assembly, added a stand with movable arm to support the tube, and mounted all of this on to a cart with wheels. Thus, the mobile x-ray unit was born (Figure 39). It was larger and more powerful, yet could be transported to the patient bedside for the exam.

MOBILE X-RAY UNIT DESIGN

The improved mobile units were still limited in power. They had to produce x-rays using the line power supplied at the facility or they had to be self-powered using internal batteries. The power restriction turned out to be the most difficult design problem to overcome. Over the years, four different designs in mobile x-ray units resulted: the line-powered unit, the capacitor discharge unit, the battery-powered unit, and the high-frequency unit.

THE LINE-POWERED UNIT

The first mobile x-ray units were line-powered. Derived from the portable handheld unit, they utilized the single-phase line power commonly available at electrical wall outlets, 110 volts AC in the USA, for example. Since they employed the most basic single phase generator design (Chapter III), the input line voltage would remain a limiting factor in x-ray outputs. Line-powered units could achieve kVp ranges starting at 40 kVp up to 100 kVp, but very low tube currents. Line-powered units could, however, perform many x-ray exams producing good quality imaging.

Manufacturers strived to create a more powerful mobile unit that could perform even more of the x-ray studies routinely performed in a fixed radiographic room. Later versions of the line-powered mobile unit were larger, heavier, but much more powerful. The components

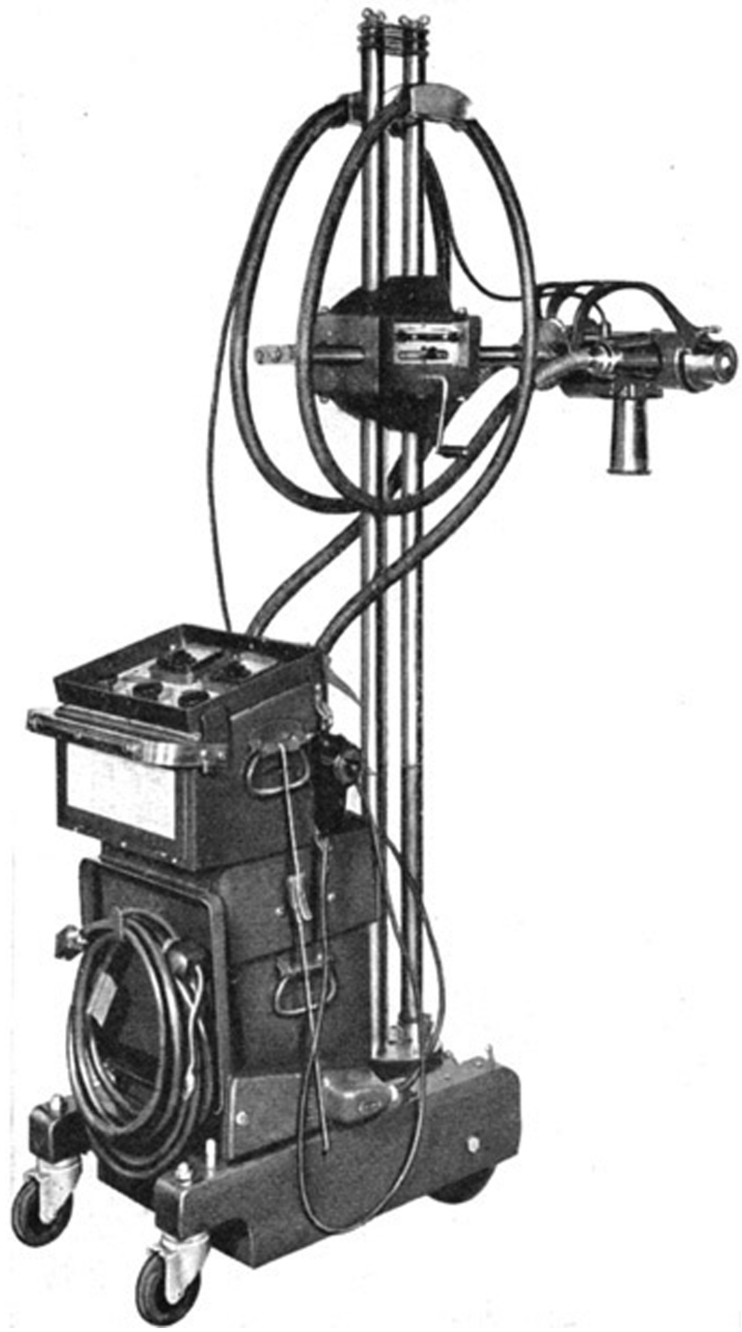


Figure 39. An Early Vintage Mobile X-ray Unit.

of the x-ray generator were larger and x-ray tubes with rotating anodes were employed. These tubes were heavier than tubes with stationary anodes, requiring a more substantial tube support with counterweights to balance the tube. These higher-powered units came at a cost: the larger size added weight which limited their maneuverability. Eventually, they required a motor drive system to aid in moving the unit around the hospital floor. Later versions of the line-powered unit included an internal battery to power the motor drive system. Now the technologist no longer had to push the unit around; it was self-powered. The drive system aided in mobility, but the batteries, motors, and associated drive system added substantial weight to the mobile unit. They were no longer fully portable.

THE CAPACITOR DISCHARGE UNIT

The capacitor discharge unit was specifically designed to address the problem imposed by the limited AC input line voltage. Rather than using direct line voltage for the exposure, these units utilized a bank of charged capacitors to develop the high voltage. Using this method, exposures at a relatively high mA could be achieved during the exposure.

These units operate differently from a conventional x-ray unit. The capacitor discharge unit is plugged into a normal AC outlet, a technique is selected, and the operator then must press a charge button to prepare for an exposure. In fact, an easy way to identify a portable unit as a capacitor discharge type is by the presence of a charge button (not to be confused with a battery charge button). By pressing the charge button, the internal capacitors were charged to a DC level that would be used to achieve a specific kVp output. When the capacitors are fully charged, the unit is ready for exposure, and, most significantly, high voltage is now present at the x-ray tube. With this type of mobile x-ray unit, the capacitors are the power source for the x-ray tube and not the line voltage.

The x-ray tube in a capacitor discharge unit is a special type of grid-controlled tube. The grid of the tube (i.e., focusing cup) has a bias voltage applied to it when the x-ray unit is turned on. When the unit is charged, the kilovoltage is immediately applied across the x-ray tube but will not, however, conduct current until the grid bias voltage is re-

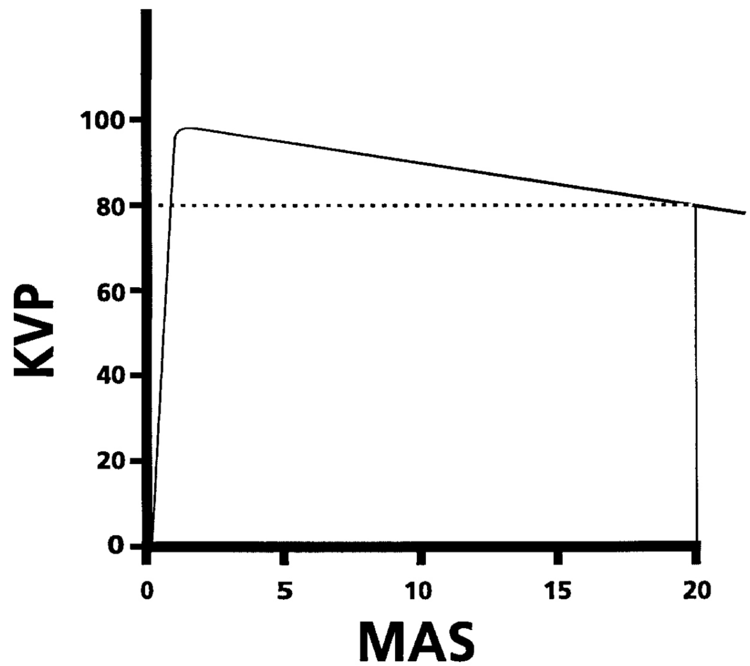


Figure 40. Capacitor discharge unit output waveform. In this typical example, the kVp decreases at a rate of 1 kVp per mAs.

moved. Depressing the preparation/exposure switch initiates anode rotation and, after a boost time, biases the grid of the tube "on" to initiate the exposure. The capacitors discharge through the x-ray tube during the exposure, producing a negative sloping waveform (Figure 40).

As the capacitors discharge through the x-ray tube, the kVp decreases at a calculated rate (1 kVp per mAs for a 1 microfarad capacitor), producing a negative sloping waveform. In addition, the actual mA also decreases during the exposure producing a similar waveform. With the output produced by the capacitors, these units can generate a relatively high technique (e.g., 110 kVp, @ 100 mA) for very short exposures. If the waveform of a capacitor discharge unit is compared to a conventional single phase unit, it will be clear that the capacitor discharge unit can produce a more constant kVp waveform, especially for short exposures.

Capacitor discharge mobile units were widely used in hospitals due to their increased outputs. However, with the improvement in battery technology, capacitor discharge units were eventually replaced by the battery-powered unit.

THE BATTERY-POWERED UNIT

The third type of mobile x-ray unit provides a good solution to the limitations imposed by line power. The battery-powered unit (Figure 41) is completely self-powered and does not utilize the AC line for power during an exposure.

The power source for the x-ray generator in this type of mobile unit is a series of high-capacity storage batteries. The batteries supply the primary voltage needed to develop high voltage for the exposure.

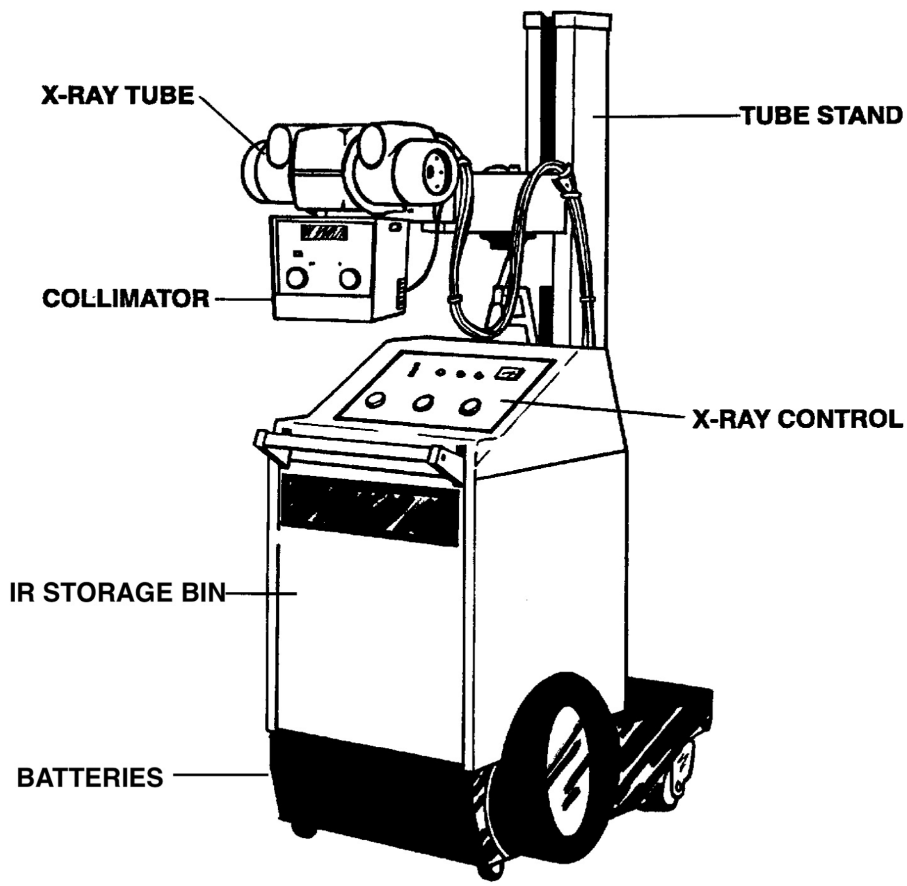


Figure 41. The Battery-powered Unit.

They also supply power to the motor drive system that is a requirement for all battery-powered mobile x-ray units.

With battery-powered units, a selected DC voltage, derived from the batteries, is converted to an AC primary signal by means of an inverter. The AC signal that is derived from the inverter is sent to the high voltage transformer where it is increased to the desired kVp setting, rectified, and applied to the x-ray tube. Most inverters on mobile units operate at low to mid frequencies (e.g., 500 Hz–1,000 Hz), delivering a constant (low ripple) output in the range from 40 kVp-125 kVp at 100 mA.

The obvious advantage to this type of mobile unit is that it can be used anywhere in the hospital, regardless of the availability of wall outlets. X-ray technicians who operate these units appreciate this feature the most. Other advantages include an increased radiation output as compared to the two earlier types of mobile units, and a low ripple kVp waveform (due to the higher frequency employed).

The main disadvantage of battery-powered units is that the batteries add significant weight to the unit. Many batteries (12 or more) are required to get the power needed to achieve the higher outputs offered by this unit. In addition, the batteries must be well maintained and properly charged. Proper battery charging protocol is a necessity, since if the batteries fail to function for any reason, the mobile unit cannot be used. In fact, if the batteries are drained, the mobile unit cannot be moved–it's just too heavy. For this reason, a battery charge status indicator is placed on the front panel of all battery-powered units so that the operator can easily monitor the charge condition of the batteries. The battery-level indicator is essential component of battery-powered mobile units. Technologists are required to check the battery status regularly to ensure that the x-ray unit is ready for use.

In addition, with battery-powered units, a battery charging protocol must be strictly followed. As with any battery, if not properly charged (and discharged), it will not perform optimally or reliably over the life of the battery. The battery charging schedule, found in the operation manual, will vary for the type of battery but, as a rule, the batteries should be charged when the unit is not being used, keeping them in a "topped off" condition. This requires the operator to store the unit near a wall outlet, usually in the hallway of the hospital, and plug it in. The unit remains charging until the next "portable" is ordered. If this protocol is not followed and the batteries are not charged regularly, they will not function to full capacity, will have reduced life, and can fail. In addition to the daily protocol, extended battery maintenance and testing should be performed periodically by a service engineer. This additional maintenance helps to keep the battery condition at an optimum. A final note on batteries. They do have a limited life: a finite amount of charge and discharge cycles. This means that they must be replaced and, most importantly, disposed of safely.

In summary, the battery-powered mobile x-ray unit is the most powerful of the mobile units, achieving tube currents of 100mA, or more. These units can produce diagnostic quality images on most patients, without having the need to plug the unit in for the exam. The greater power that these machines achieve comes at a cost in energy (constant battery charging) and to the environment (battery disposal). Since many x-ray examinations can be performed with lower tube currents, there is less demand for these larger units. With the rise in use of digital receptors, they may even become obsolete. At a time when, globally, we are moving to be energy efficient and "green," the battery-powered unit may go the way of the dinosaur.

THE HIGH-FREQUENCY MOBILE X-RAY UNIT

As mentioned earlier in this chapter, there has been an increased need for mobile x-ray services, largely driven by an aging population. Today, there is a great demand for home studies, for example. To move a mobile unit in and out of a vehicle, and to transport it on the road, it must be lightweight and compact in design. To directly address these issues, two recent design changes to the basic, line-power mobile unit have allowed for the rise in popularity and increased use of the line-powered unit: a high-frequency generator and a smaller x-ray tube, attached to a lightweight cart (Figure 42).

The x-ray generator has been updated from a single-phase generator to a high-frequency generator (Figure 43). The compact design includes the x-ray tube, the high-frequency generator and collimator in one tube head assembly. The newer, lightweight (e.g., 20–30 lbs.) high-frequency generators allow for much higher outputs, from 40 kVp to 120 kVp, at higher tube currents (15-50 mA) yet still operate from the standard wall outlet. This advancement, combined with DR

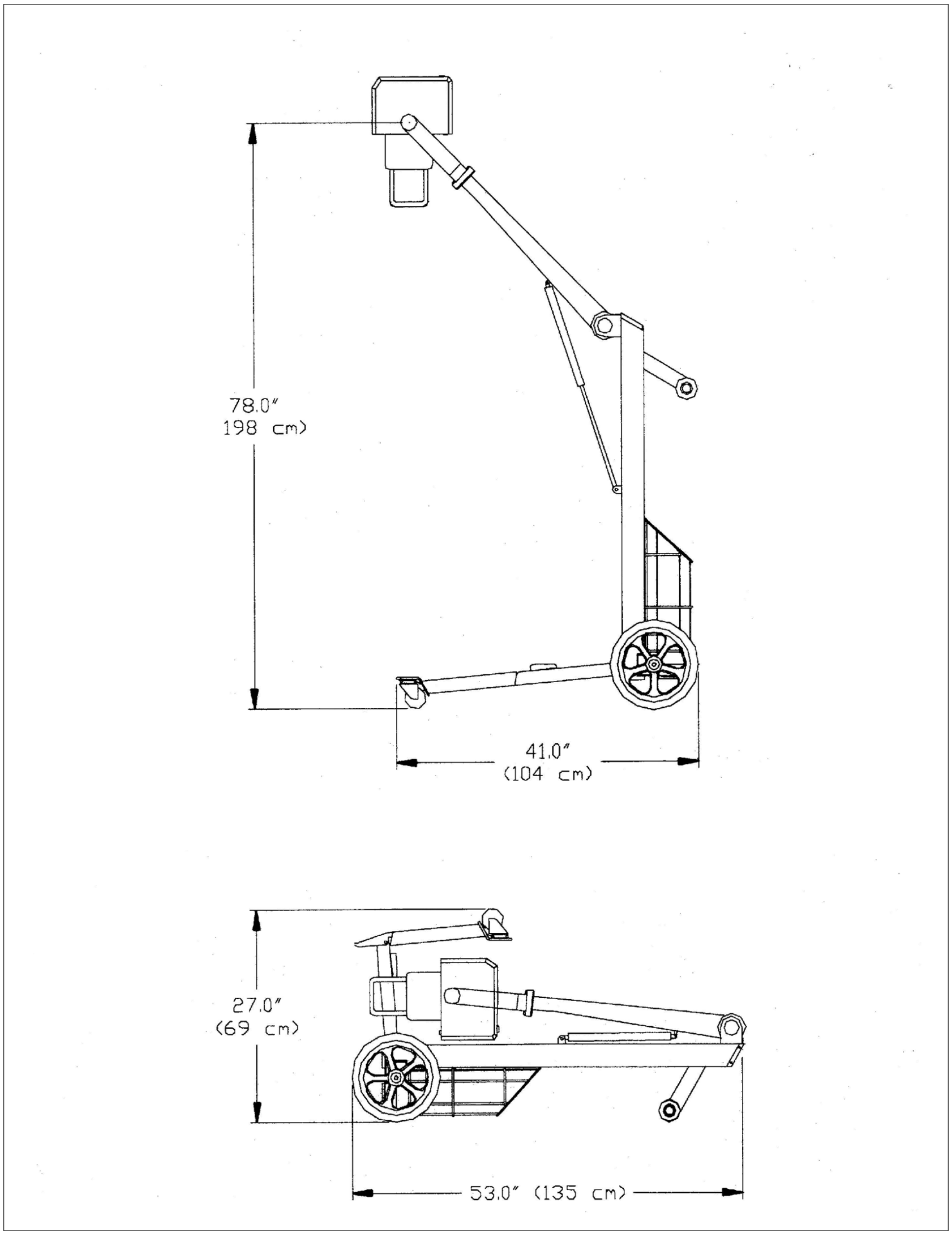


Figure 42. A Lightweight High-Frequency Mobile X-ray Unit.

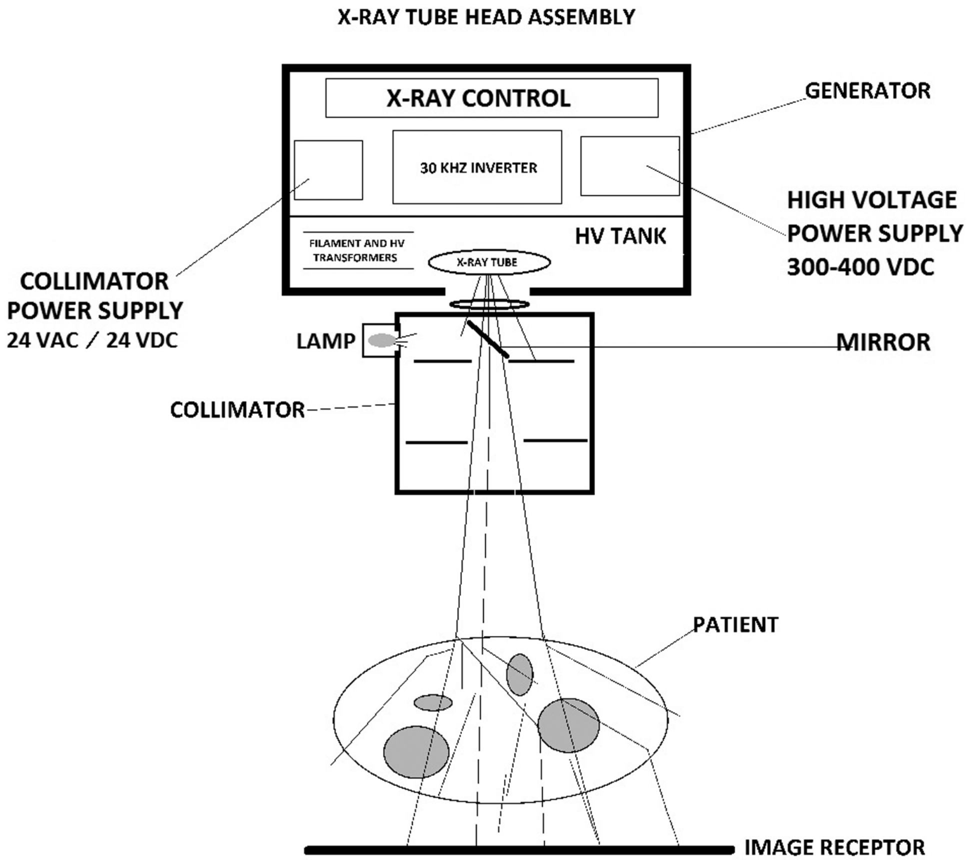


Figure 43. The High-Frequency Mobile X-ray Tube Head Assembly.

technology, has transformed the original line-powered unit into highly versatile machines that can perform most radiographic exams at remote locations including nursing homes, prisons, offsite medical facilities, urgent care centers, and private homes. They can perform in a hospital setting as well. Their compact design makes them much more maneuverable, especially in tight quarters such as in a hospital ICU, or in the Emergency Room. They also move easily up and down stairs. And the greatest advantage of all is that the newer line-powered units can be purchased at a fraction of the cost of a battery-powered unit– $10,000 for a high-frequency line-powered unit vs. $200,000 for battery-powered unit, as of this writing.

FAILURES WITH MOBILE X-RAY UNITS

Since a mobile unit is a radiographic system (on wheels), it will experience the exact same kinds of problems that occur with any radiographic equipment. However, because of their specialized design, mobile units will experience a few additional types of failures. All mobile x-ray units will experience problems with the line power cord, the exposure handswitch, and the batteries used both for producing radiation and to power the drive motors used for transport. In addition, capacitor discharge units will experience unique problems also because of their special design.

The most common failure with mobile x-ray units is a result of a damaged AC line power cord. Line-powered units and capacitor discharge units must be plugged into an AC outlet to produce radiation. These units are equipped with unusually long power cords (much longer than the standard 15 feet for medical equipment) which are often difficult to store. Consequently, the power cord often becomes tangled and unduly stressed. Moreover, the power cords are usually left lying on the floor while the mobile unit is being used and they will invariably get run over by various equipment, including the mobile unit itself. Because of the excessive stress, the power cord and plug are regularly damaged.

Also, since battery-powered units must be plugged into an AC outlet when not in use the power cord gets a lot of handling. The process of plugging and unplugging these units will, over time, eventually damage the pins of the plugs. To make matters worse, technicians often attempt to move the mobile unit, forgetting to first unplug the power cord. This practice will severely damage the plug and line cord. It is easy to understand why this is a high failure area, but it is also easily corrected.

The exposure handswitch will also fail frequently on mobile x-ray units. As with the power cord, the cable connecting the handswitch to the x-ray control is also unusually long, extending to 10 feet or more. Consequently, similar damage occurs to the handswitch cable. When exposing the patient during the examination, the technologist will stand behind the mobile x-ray unit, stretching the exposure cord while stepping back to achieve a safe distance from the radiation source. An action that can stress the exposure cord. In addition, the handswitch is usually stored in a plastic holder or hung from a hook mounted on the mobile cart when not being used. Here, gravity holds the handswitch in place. With this design, the handswitch can be easily knocked out of the holder and break.

As mentioned above, a common failure in mobile units occurs with the internal batteries. The batteries must be properly maintained or they will fail. As a typical scenario, a technologist will inadvertently forget to plug in the mobile unit when he or she is finished using it, or the line cord (or plug) may be broken so that even though the technician plugs the unit in, the batteries will not receive a charge. In either case, this is detrimental to the battery life. With most batteries, if they become discharged and left in an uncharged state for a period of time, they will begin to lose the ability to hold a full charge. Because it is difficult to ensure that the batteries are being optimally charged, many manufacturers of mobile units recommend that these batteries be replaced at least once every two years. The batteries should be replaced even if they appear to be functioning properly at that time. This practice greatly reduces mobile unit down time.

The other failure in mobile units is unique to capacitor discharge units. With these units, the high voltage capacitors, located in the high voltage tank, store the total kilovoltage charge for the exposure. These capacitors typically will begin to leak current over time and will not be able to hold a complete charge. In addition, the capacitors could become resistive over time. When this occurs, the secondary circuit will be essentially shorted, and the resulting high current draw will cause the line fuse to blow.

Another unique feature of capacitor discharge units is that they use a special grid controlled x-ray tube. When the charge button is depressed on the control, the unit will charge to the selected kVp which is then directly applied across the x-ray tube. A bias voltage placed on the grid of the x-ray tube will inhibit conduction and, therefore, the production of radiation. When the handswitch is depressed, the bias voltage is removed from the grid via a grid bias switch. The grid switch, because it is in the high voltage circuit, can fail after a period of use.

Chapter XI

TOMOGRAPHY

OVERVIEW

Many of the techniques used in general radiography are effective at obtaining diagnostic quality images of the internal structures of patients. General radiographic techniques are employed when imaging the bones of the extremities or of the lungs, for example, when the desired anatomy is relatively unobstructed. However, certain structures in the human body cannot be directly imaged because they are partially or totally hidden by overlying organs. Also, the desired structure may lie in an area within the body that is surrounded by similar tissue. In these cases, special radiographic techniques are required to obtain images of the obstructed organs.

The organs that comprise the digestive system, for example, are surrounded by tissue of similar density and are very difficult to discern with normal radiographic techniques. Also, some of these organs are hidden by other structures within the body when viewed from an anterior-posterior (AP) projection. One method used to view obstructed organs is by using contrast agents. When introduced into a structure such as the stomach, a contrast agent will highlight that structure only on the final image. Contrast agents are commonly used in fluoroscopic and angiographic procedures to help with the diagnoses of structural anomalies found in the circulatory and digestive systems.

But for general radiographic procedures, another technique can be used to view structures hidden within the body. It is nearly impossible, for example, to obtain good images of the kidneys by using conventional radiographic techniques because of the presence of overlying organs. In a standard AP projection, the organs of the digestive tract obstruct the view of the kidneys and will be superimposed on the image of the kidneys. Other examples of structures difficult to image in general radiography include the sternum (AP view), thoracic spine (lateral view), and the gall bladder.

The easiest solution when imaging an obstructed organ would be to focus the x-ray beam solely on that organ. If, for example, the x-ray beam could be focused to the single plane within the body in which the desired structure lies, the resulting image would be of that structure only, regardless of the surrounding organs. This plane specific focusing is accomplished through tomography.

Tomography is a specialized application of radiography in which a section or "slice" (tomos in Greek) of a patient is imaged. Invented in the early 1920s, body section radiography was perfected in 1929 by Jean Kieffere, a radiologic technologist working in the United States. Many other terms have been used to describe sectional radiography, including planigraphy, laminagraphy, and stratigraphy, however, tomography is the term most commonly used today. In effect, tomography allows the radiologist to view a single slice of anatomy at any depth located within the patient's body.

APPLICATION

Once a preferred diagnostic tool for many studies, today conventional tomography has limited uses. With the advent and refinement of CT (computed tomography), many of the procedures once performed using conventional tomography are now being performed on CT scanners. In fact, most of the larger medical institutions regularly employ CT scanners to perform sectional studies. Today conventional tomography is confined to only a few specific types of studies, which includes studies of the kidneys, especially IVPs (Inter-Venal Pyleography) and KUBs (Kidney, Ureter, urinary Bladder) studies. These procedures are still performed routinely and provide a valuable means to diagnose kidney and urinary functions.

PRINCIPLES OF TOMOGRAPHY

The main goal of tomography is to maintain the precise focusing of a section of anatomy located at one depth within the patient. This goal is accomplished by blurring the surrounding structures. It is helpful to think of tomography in reverse terms. Rather than "focusing" on a structure lying in a specific plane, the goal is to blur the undesirable surrounding structures, instead, so that only the desired structure will appear focused on the final image. Tomography blurs out the anatomy lying above and below the desired plane, thus emphasizing the specifically targeted structure. The blurring effect is accomplished by utilizing the effects of motion.

As with any radiographic procedure, the patient should remain reasonably motionless during the x-ray exposure so that the radiologic technologist can obtain a sharply focused image. This is true for tomography, as well. To create the blurring effect, the x-ray tube and image receptor are set into motion. The tube/receptor motion takes place during the exposure while the patient lies completely still on the x-ray table.

Over the years, several types of tube/receptor movements have been utilized to obtain this blurring effect, including circular motions, vertical motions, and even spiral movements. However, the preferred method is one in which the x-ray tube moves in a straight line, parallel to the tabletop and image receptor. This type of tomography, termed rectilinear tomography (or linear tomography), has proven most effective in producing quality tomographic images. Furthermore, a linear tomographic unit is simplest in design and cheapest to manufacture.

The principles of tomography are more easily understood when visualizing the tube/receptor assembly as a fulcrum moving about a pivot point (see Figure 44). The tube and receptor are physically connected to each other and pivot about a central point located on a tomographic table. The tomographic table is specifically designed to accommodate this modified tube/receptor assembly. In the most basic design, the x-ray tube is mechanically attached to the image receptor cabinet with a solid metal connecting rod. A point located at distance halfway between the image receptor and x-ray tube becomes the pivot point, or fulcrum. When the x-ray tube is moved to the right (viewed from the front of the table), the Bucky will move in the opposite direction and at the same speed as the x-ray tube.

In tomography, the x-ray tube and receptor must move simultaneously, at the same speed, and in opposite directions while the x-ray beam remains centered on the image receptor. Since radiation travels

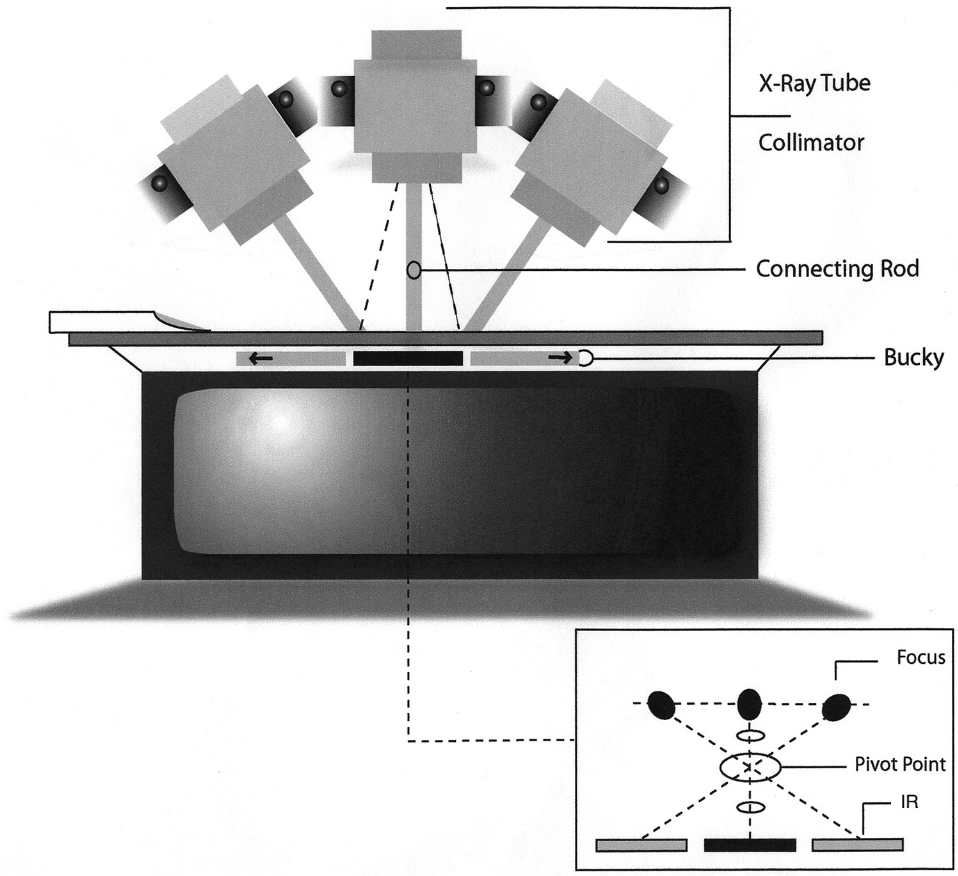


Figure 44. The tomographic table.

in straight lines through air, the connecting rod can be used to represent the central portion of the x-ray beam. The diagram (Figure 44) shows how the beam will remain centered on the image receptor throughout the entire range of motion.

The pivot point is the exact point of focus of the x-ray beam. Only objects located at the fulcrum will be focused on the image receptor during a tomographic exposure sweep. Structures that lie immediately above or below this point of focus will be blurred because their shadows will move at different speeds in relation to the speed of the shadow of the object located at the focus. The inset of Figure 44 demonstrates that a structure located at any point above the plane of the focus will cast a shadow that moves faster than the shadow of the structure located in the focus plane; the shadow of structures below the focus plane travels slower (a line drawn from the x-ray tube focus through the upper or lower structure will help to demonstrate this phenomenon). Both upper and lower structures will appear blurred on the image.

In a tomographic study, the pivot point is positioned at the plane within the body in which the desired structure lies. In this way, only that structure will appear focused on the image even if surrounded by similar tissue. That plane, which is parallel to the image plane, is referred to as the objective plane. The pivot point (or focus) can be moved up or down through any objective plane within the patient's body. Specifically, if a patient is lying on the x-ray table in the supine position, the pivot point can be raised to the height of the sternum, or it can be lowered to the vertebral column located just a few millimeters above the table top.

When preparing for a tomogram, the radiographic technologist must consider two important variables: the exact location of the structure and the desired thickness of slice. First, a measurement is taken to determine the exact location of the desired section of the structure to be imaged. The technologist uses this measurement to set the tomographic height. The tomographic height setting is, again, the fulcrum height and pivot point. The technologist sets the tomographic height by moving the fulcrum to the exact measured distance. Now the pivot point is positioned precisely at the level of the desired anatomy and will not move during the exposure.

With tomographic height set, the technologist must adjust for how thick a section of anatomy is required for the study. The tomographic thickness, prescribed by the radiologist, will vary depending on the type of examination. Tomographic thickness is, in effect, the area of greatest sharpness within the imaged structure. When viewing a tomographic image, objects very close to the tomographic height setting will appear relatively sharp. Moving away from the focus, image blurring gradually increases to a point where the anatomy becomes so blurred that it appears as background noise. The tomographic thickness can be set so that the entire structure appears sharp on the final image, or slice thickness can be set to view a section as thin as a few millimeters.

Using reverse terms once more, increasing the amount of blurring of tissue located immediately above and below the desired structure will create the effect of a thinner section. Decreasing the amount of blurring will result in a thicker section that will remain in focus. Slice thickness is controlled by the amount of blurring that is created.

The way to control section thickness is by varying the distance that the x-ray tube travels during a tomographic excursion. Essentially, the greater the movement of the x-ray tube the more the blurring effect is exaggerated. When the x-ray tube is directly overhead, for example, the tube/Bucky axis is perpendicular to the table, or at zero degrees. In this setup, which is normally used in general radiography, the focus approaches infinity. During a tomographic sweep, however, the tube will begin at some point towards the head end of the table and move an equal distance through the zero point to a point at the foot end of the table. It is this motion that creates the blurring effect and by controlling the amount of motion, we can accurately control slice thickness.

To maintain exact focusing of the x-ray beam on a given structure during a tomographic sweep, the x-ray tube must rotate as it travels along its path. As the x-ray tube travels along the length of the table, it is rotated to remain aligned to the image receptor. Moving the tube towards the head end of the table a given distance will cause the x-ray tube to rotate to a corresponding angle, for example, minus 20 degrees. Moving the x-ray tube towards the foot end of the table to an equal distance from the perpendicular (0 degrees) will cause the x-ray tube to pivot to an angle of plus 20 degrees.

The tube angle therefore directly relates to the sweep distance. In tomography, instead of adjusting the sweep distance, the tomographic thickness is set by adjusting the tube angle, or tomographic angle. At large tomographic angle settings, the x-ray tube will travel a significant distance, which will create an image of a thin section of anatomy. Smaller tomographic angle settings result in little movement and thicker sections (see Appendix G).

For example, starting at an angle of minus one degree, the tube must travel one degree from the head end of the table to return to zero, then must travel through zero to plus one degree. The total movement is two degrees. Since this motion is minimal, most of the objects in the path of the beam will be sharply focused, similar in appearance to a general radiograph. Smaller angle sweep settings of ten degrees or less result in a relatively thick section or "zone" being imaged. A tomographic technique using small angles is sometimes termed, zonography. Zonography is very useful when the obscuring structures are far from the objective plane, or when the entire organ is to be imaged.

Continuing with our example, moving the starting point to 20 degrees at the head end of the table, the x-ray tube now travels from minus 20 degrees through zero to plus 20 degrees for a total sweep of 40 degrees. The tube/Bucky assembly now moves a significant distance, resulting in a greater amount of blurring. By increasing the tomographic angle setting even further to 40 degrees, the tube will travel a much greater distance along the table for a total sweep of 80 degrees, which will create an extreme amount of blurring. In this case, only a very thin plane measuring a few millimeters will be in focus on image plane. Thus, linear tomography allows for complete control of the slice depth and slice thickness. In tomography, only a few standard tomographic angles have proven effective for most studies. As a rule, a conventional tomographic unit will provide settings for 10 degree, 20 degree, and 40 degree tomographic angles.

Another parameter in tomography that must also be considered is the speed at which the tube travels during a tomographic sweep. The tomographic speed is set by the technologist to accommodate the individual patient's needs. Every tomographic unit provides a fast and a slow speed setting for x-ray tube/receptor movement. Fast tomography techniques are most often used when short exposure times are needed, such as for pediatric cases, or when the patient is experiencing pain and cannot remain motionless for long periods of time. The faster speed helps reduce patient motion which can detract from image quality. At slower sweep speeds there is less vibration and smoother motion, which helps produce improved image quality. Ideally, slow speed should be used whenever possible.

When discussing linear tomography, there are a few issues concerning the images that are produced that should be mentioned. In general radiography, the x-ray tube is positioned directly over the organ to be imaged in an AP/PA projection, and the tube remains motionless during the exposure. This setup will always produce the sharpest image. Since the tube/Bucky assembly is in constant motion during the tomographic exposure, the resulting images will be slightly distorted and minor streaking may appear on the image. Furthermore, in some instances, the final image can appear elongated in the direction of tube motion. These detracting effects to the image are a direct result of the tomographic process and are, unfortunately, unavoidable. Also, the images of other structures within the body can appear superimposed on the desired structure, depending on how close they are in respect to that structure. There is an art to obtaining a good tomographic image.

TOMOGRAPHIC EQUIPMENT

A tomographic unit is a slightly modified general radiographic unit. The equipment in a tomographic suite is identical to that found in a general radiographic room with important exceptions found in three areas: the x-ray table, the tube support, and the x-ray generator.

The Tomographic Table

As discussed in Chapter IV, the radiographic table is a specialized table that aids in patient imaging. In addition to the standard mechanical devices found in all radiographic tables, a tomographic table must include a mechanical means of connecting the x-ray tube to the image receptor. This physical connection ensures that the x-ray tube and image receptor move simultaneously and at the same speed. Additionally, tomographic tables also require an electromechanical means to control the precise movements of the tube/receptor assembly. A motor drive assembly is required, as well as the associated electronic circuitry to control the tube/receptor motion.

With tomographic tables, the x-ray tube and image receptor are physically connected by either a permanent column, or by a connecting rod. The use of a connecting rod is often preferred since it is removable, allowing the equipment to be used for general studies. In the most basic design, the connecting rod is a steel rod or bar. In this design, the connecting rod is attached to the table and x-ray tube prior to the tomographic examination and is removed and stored within the x-ray room for general radiographic studies. Some equipment designs allow for the rod to be permanently attached to the x-ray tube assembly. In this case, the rod is disengaged for general use.

The connecting rod attaches the image receptor, located under the tabletop, directly to a tubestand or an overhead tubecrane, and is commonly held in place with either a spring pin, or locking knob. The tube support must have a means of sensing the attachment to the table, and the additional circuitry that disengages the x-ray tube's lateral and rotational electromagnetic locks when connected, putting the table in "Tomographic Mode." Once the connecting rod is secured, the tube/Bucky assembly move as one unit. A motor drive system, located within the tomographic table, now controls the tube/Bucky movement. The motor drive assembly, which includes a motor and its associated gears and linkages, allows for precise positioning and braking of the tube.

The tomographic mode is selected at the x-ray control (or control panel at the table) by the technologist to engage the gears and prepare for the tomographic examination. The control panel provides the tomographic technique selections for tomographic angle, sweep speed, and slice thickness. In addition, all tomographic controls provide a test switch that allows the operator to perform a tomographic test sweep without the use of x-rays.

The tomographic table must also have a means of identifying the position of the x-ray tube and the Bucky. A common way to detect and control this motion is by means of a series of microswitches or photo sensors. Located just below the tabletop, these sensors detect the tube/Bucky position and can be used to control the length of the tomographic excursion. Furthermore, elevating tables require an additional exposure interlock microswitch to indicate that the table is at the correct exposure height for tomography.

As will be discussed later in the chapter, the mechanical linkages between the x-ray tube and image receptor will wear over time and can become a source of imaging problems. In response to this weak link in the system, newer equipment designs have eliminated the connecting rod altogether, using instead a fulcrumless system. Fulcrumless systems utilize separate motors for x-ray tube and Bucky movements, eliminating the need for any physical connections between the components. The individual motors are controlled by software, which provides accurate and smooth operation.

The X-ray Generator

The x-ray generator used for tomography is the same as that used in general radiography, with a few additional specialized components.

In fact, many generators used for general radiography can be easily upgraded for special radiographic applications such as for tomography. Generally, a tomographic x-ray generator will include a special function switch on the console, which enables the tomographic mode of operation. When in “Tomo” mode, the appropriate x-ray tube and receptor are activated. Tomographic generators also provide a wider range of mA selections.

An important consideration for tomographic generators relates to the extended exposure times needed for an exam. During a tomographic excursion, the x-ray tube can move several feet or more as it travels from the head end to the foot end of the radiographic table. More importantly, x-ray radiation is being emitted during most of that excursion so that exposures can be as long as five seconds in duration. Therefore, the x-ray tube and generator must be able to accommodate these longer exposure times. To ensure that the heat and exposure limits of the x-ray tube will not be exceeded, tomographic studies use of very low mA technique settings. Consequently, all tomographic x-ray generators must have the capability of providing these significantly lower mA settings and longer exposure time settings.

The x-ray generator should provide a selection of 25 mA (or lower) on the small focus of the x-ray tube. At these lower mA settings, the longer exposure times can easily be achieved without the risk of damaging the x-ray tube. Accordingly, tomographic techniques commonly provide settings of 5 mA, 10 mA, 15 mA, and 25 mA.

OPERATION

For a tomographic study, the patient is positioned on the tabletop so that the desired anatomy is centered directly over the image receptor. The plane of the structure is measured (referenced to the tabletop) and the fulcrum is set to that distance. A scout film (i.e., normal AP/PA radiograph) is taken to ensure that the kVp technique setting is correct, and to verify positioning. The operator then selects “Tomo” mode on the x-ray console and programs the tomographic angle and speed on the tomographic control. At this point, a test run (i.e., tube excursion without x-ray radiation) can be performed to ensure that the unit is working as programmed and that there are no obstructions in the path of the x-ray tube.

Next, the x-ray tube is moved to the starting point for the tomographic sweep. The exposure is initiated at the x-ray control via the exposure handswitch which sets the tube in motion. Since smooth movement is essential to obtaining a quality tomogram, the x-ray tube should be moving at constant speed prior to emitting radiation. Once the tube reaches the programmed tomographic angle, the exposure begins. The exposure terminates as programmed by the x-ray timer, or when the tube finishes its sweep and braking is initiated.

CALIBRATION

To calibrate a tomographic unit, the service engineer should first complete all the calibration procedures required for general radiographic equipment as described earlier in this book. During the calibration the engineer should focus specifically on two areas that directly concern tomography: the lower range of mA calibrations and the tomographic table adjustments.

The service engineer should take extra care when calibrating the lower mA stations to ensure the tube current waveforms at 5, 10, 15, and 25 mA are stable for the entire duration of the exposure. The reason for this is twofold. First, it is generally difficult to obtain a stable waveform at low current settings because of the inherent characteristics of the x-ray tube. The engineer should spend extra time in this area. Second, with the longer exposures required for tomography, as much as 5 seconds, there is a greater chance of waveform fluctuations because of fluctuations and noise occurring on the incoming, single phase line. The use of an oscilloscope when calibrating the mA stations is highly recommended to ensure proper adjustments. Once each mA station is calibrated, the engineer should observe the mA waveforms on the oscilloscope during longer exposures to verify calibration.

The engineer should also concentrate on the calibrations of the tomographic table. For precise imaging, the following parameters should be calibrated: fulcrum height, sweep speed, and tomographic angle. Since the designs of tomographic tables can vary, general calibration principles are described below.

The fulcrum height is adjusted so that when, for example, the fulcrum height indicator displays five centimeters, the true focus is exactly 5cm above the tabletop. Essentially, what is being calibrated is the height indicator readout. The service engineer will measure above the tabletop a given distance and calibrate the readout to match the actual setting. The adjustment should be verified with a test image. To do this, a phantom should be placed on the tabletop and then exposed. Most tomographic phantoms are designed with incremental steps that are clearly marked with lead numeric markers. If a 5 cm fulcrum height is set, for example, then the number "5" will appear in focus on the image and numbers "4" and "6" should appear blurred.

Sweep speed is adjusted in various ways. In basic designs, the speed is set by first measuring the actual time it takes to make a full sweep, and then by calibrating the sweep time to manufacturer's specifications. A stopwatch is normally used for this calibration. Tomographic angles are measured, and then adjusted by changing the locations of the corresponding microswitches or electronic sensors. In many instances, these angles are fixed and field adjustments are not required.

FAILURES WITH TOMOGRAPHIC UNITS

Generally, whenever excessive movement is involved with radiographic equipment, predictable failures will occur because of those movements. If the x-ray tube is repositioned frequently, as it is in general radiography, the interconnecting cables that attach to the x-ray tube tend to be stressed. Because of the repeated motions associated with tomography, the stress on these interconnecting cables is exaggerated. Eventually, these cables will become damaged or the connectors can become dislodged or broken. Accordingly, on every preventive maintenance, the service engineer should carefully inspect the condition of these cable harnesses, and the cables that attach to image receptor, looking for loose connectors and worn insulation.

Another common mechanical failure occurring with tomographic units is likewise a result of the routine movements of the tube/Bucky assembly. Without question, the single most important criterion for tomography is that tube and receptor remain vibration-free during the exposure. Specifically, the amount of "play" in the mechanical linkages must be minimal to produce a quality image. Play in the linkage causes uneven or lost motion that will result in unwanted blurring on the final image. A loss of image quality is most noticed when the play develops at the fulcrum of the tomographic table, since the effects of lost motion will be magnified here. This undesirable blurring will also occur when the play occurs at the Bucky linkage. Lost motion has minimal effect when it occurs at the x-ray tube.

Because of the effects of lost motion, the number of linkages should be kept to a minimum with equipment design. Regardless, image quality problems often result from a worn or damaged linkage in the tube/Bucky assembly. The engineer should, therefore, routinely inspect the tube/receptor assembly during a preventive maintenance inspection and should make the appropriate adjustments or repairs when necessary.

The microswitches used to detect the tube/receptor movements are also prone to failure especially with equipment that utilizes mechanical switches and detents. These components simply wear down with normal use and require frequent adjustments. Systems that employ magnetic or photo sensors are less problematic.

As mentioned earlier in the chapter, the best equipment designs utilize fulcrumless systems that employ separate microprocessor controlled drive systems for both the tube and the Bucky movements. With these systems, the x-ray tube and image receptor do not have a physical connection. Therefore, there are no linkage-related problems. Fulcrumless systems have greatly reduced the potential for lost motion.

Chapter XII

MAMMOGRAPHY

OVERVIEW

Mammography is a specialized field of radiography developed specifically to help in the diagnosis of breast-related cancers. Cancer is second only to heart disease as the leading cause of death in women. Consequently, it is recommended that all women undergo breast screenings regularly after the age of 50–age 40 if there is a family history of breast cancer. Since mammography x-ray systems produce high-quality breast images, it is the first choice for effective screening for breast cancer.

Since first developed, mammographic equipment design has undergone significant changes–many improvements a result of the MQSA (Mammography Quality Standards Act), which, in 1994, established specific guidelines for mammography. Each component in the mammographic system has been adapted from those used in general radiography to produce high quality images of soft tissue. These include the x-ray tube, the collimator, filtration, the tube support, and the image receptor. Still, mammography follows the basic principles of radiography so the service engineer can easily adapt to servicing mammographic equipment.

Because of the composition of breast tissue, much lower x-ray techniques (kV, mA, and time) are needed to obtain diagnostic images. Also, the quality of the x-ray beam, the type of grid, and the means of image capture and processing have been modified to achieve good images of the breast. Even the reading room and viewing monitor used by radiologists for diagnosing images had to be altered to enhance the visualization of fine details in breast tissue. Moreover, mammography technologists must follow stringent quality control measure to verify equipment calibrations and to ensure consistency in image quality. Because of the many regulations involved with mammography, the service engineer must remain current on the latest MQSA guidelines so that he or she can service mammography equipment effectively. In addition, he or she should be completely familiar with specific equipment designs employed in mammography, noting how each component affects the final image. Finally, a general knowledge of breast anatomy is extremely beneficial for engineers, especially when discussing imaging issues with the hospital staff.

This chapter begins with an overview of breast anatomy and describes specific techniques commonly used during a mammographic exam. Next, mammographic equipment design is discussed in detail, focusing on the components that help produce diagnostic images of the breast. An overview of calibration procedures is followed by a discussion of common failures that occur with mammography equipment.

BREAST ANATOMY

The human breast is comprised of several types of soft tissue–each with varying densities, which presents some unique imaging challenges. The main structure is the mammary gland, which consists of 15 to 20 lobes, each with numerous related ducts and lobules. The individual lobes of the mammary gland open into the lactiferous ducts, all of which converge at the nipple. The body of the mammary gland is imbedded within fatty tissue, is supplied by a network of blood and lymph vessels, and is supported by connective tissue. Furthermore, the range of tissue densities is even greater with malignant breast tissue. Both the radio-dense tissue (e.g., fibrotic tissue, glandular tissue, and malignant tissue) and radio-lucent tissue (e.g., fat or loose connective tissue) must be clearly visible on the mammogram so that the radiologist can make accurate diagnoses. To image all of these tissues properly, a mammography system must provide very low kVp techniques, in the range of 20-40 kVp, at relatively high mA/mAs outputs. In addition, extremely small focal spots (0.1-0.3 mm) must be used to image the very fine microcalcifications.

MAMMOGRAPHIC VIEWS

Since the service engineer cannot directly observe a patient during a mammographic examination, it is beneficial to understand exactly what is taking place during that procedure. This knowledge is essential for troubleshooting mammography problems and when discussing image quality issues with the staff. When investigating imaging problems, the engineer must rely on the information provided by the technologist and from the clues discerned by reviewing a questionable image. Possessing knowledge of examination protocol gives the engineer a distinct advantage when troubleshooting and also communicates service professionalism.

As a rule, a routine mammographic screening examination requires a minimum of two exposures per breast. All exams should include imaging in two planes: the Mediolateral Oblique (MLO) view and the Cranial Caudal view (CC). With these two "standard views," the radiologist should have enough visualization of tissue to provide reliable diagnoses of breast abnormalities. Additional views should be used only when standard views are inconclusive. Some additional views include a spot compression view, a magnification view (see below), a 90-degree lateral view, and a rolled view.

The MLO projection is performed at a 30 degree to 70 degree inclination from the vertical and provides good visualization of the entire breast. Most carcinomas can be identified in this view. The MLO view is supplemented with the CC view, which allows full visualization of the entire body of the mammary gland. In a CC view, the x-ray tube is positioned directly overhead, with the beam traveling from superior to inferior.

Tissue compression is used with all procedures for reasons described later in this chapter. With standard views, the compression paddle must match the size of the image receptor and full field collimation is utilized to image the entire breast. However, occasionally there is a need to spread a small area of the breast tissue to help differentiate superimposed structures. In this case, spot compression is used. The compression paddle (or cone) used in spot compression is much smaller than a standard compression paddle, measuring as small as 7 cm. In addition, spot compression is performed with the x-ray beam collimated down to the area of interest only.

In addition to the spot compression view, a magnification technique can be used to help visualize a questionable area of the breast. When performing a magnification view, a magnification table is placed above the image receptor, raising the patient's breast to a fixed distance above the image plane. The gap created between the breast and image receptor results in a magnified image of a specific area of the breast. The small focus of the x-ray tube is always used with magnification techniques and the exposure field is collimated to the specific area of interest. With magnification, the grid is removed. Scatter radiation is reduced, instead, by means of an air gap, which is created within the magnification table and by collimating "down" to the area of interest only. Spot compression is often used with magnification technique.

THE MAMMOGRAPHY UNIT

A mammography unit should meet certain requirements to produce a good quality mammogram. The unit must have sufficient power to image breasts varying in size and density, while using a minimum amount of radiation. It should produce sharp images of the extremely fine microcalcifications located within the breast tissue and must be also provide precise angulation needed to acquire the standard views that are required to visualize the entire breast tissue. As mentioned earlier, tissue compression is required for each examination so "mammo" units must provide a compression paddle and drive mechanism to compress the breast. All mammo units should provide image magnification. Finally, mammography units should be designed to handle high patient loads yet be compact to facilitate installation in imaging suites with limited space.

A mammography unit is a completely integrated x-ray system designed as a stand-alone unit. Each device normally found in a general x-ray room has been modified and consolidated into one single unit (see Figure 45). The x-ray generator, x-ray tube, tube support, collimator assembly, filter assembly, compression assembly, and the image receptor are all part of the mammographic unit. In this chapter, the mammographic unit is broken down into three sections: the gantry assembly, the c-arm assembly, and the x-ray control or work station.

The Gantry

The gantry is an integral part of a mammographic x-ray unit since it houses many of the system's components. It also provides the structural support for the c-arm assembly, which supports the complete imaging chain. The gantry must be made of a heavy steel framework to support the significant weight of the c-arm and to provide smooth, precise movements of the x-ray tube and image receptor during the examination.

Included within the gantry are the motors, gears, and associated electronic circuitry needed to control the c-arm movements. The power supplies for the system, as well as the image processing circuits are housed within the gantry. Finally, the gantry contains the complete x-ray generator.

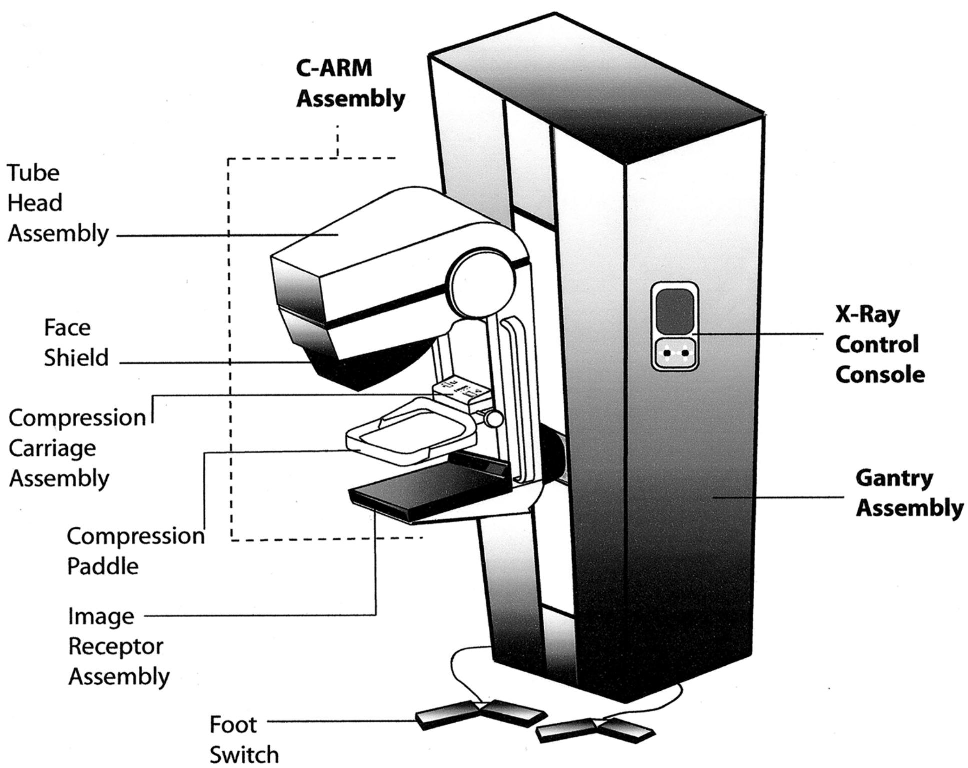


Figure 45. The mammographic system.

The X-ray Generator

For many reasons, the x-ray generator of choice used for mammography is the high-frequency generator (see Chapter III). High-frequency generators are extremely reliable, require input voltages commonly found in most hospitals and clinics, and, more importantly, take up very little space. Also, since mammography utilizes x-ray techniques that are comparably much lower than those used for general radiography (20–40 kVp @ 30–100 mA), the high voltage transformer is relatively small is size. This small footprint helps contribute to the compact design of mammography units.

The high voltage transformer is conveniently located in the base of the gantry, with the generator's primary components located on a chassis within the mainframe, or fastened to a side panel of the gantry. With this layout, the interconnecting cables are run internally, which allows for shorter cable runs and helps provide cleaner appearance of the unit. The high voltage transformer is connected to the x-ray tube, often with a single high voltage cable. With the single cable design, only one insulated cable is needed to carry both anode and cathode voltages to the x-ray tube, which also aids in the compact design of these units.

The C-Arm Assembly

With all mammography units, the x-ray tube is physically attached to the image receptor by a single rigid column utilizing a common c-arm design. Referring to Figure 45, the x-ray tube is mounted to the c-arm column at one end and the image receptor at the opposite end, always at a fixed SID (typically 65 cm). The c-arm, supported by the gantry, can be raised or lowered to adapt to the individual patient height.

In addition, the c-arm can be rotated to the precise projection angles required to visualize the components of the breast. In fact, the c-arm can be rotated to nearly 360 degrees of angulation. The c-arm assembly contains the entire imaging chain which includes the x-ray tube, filter assembly, collimator assembly, compression paddle assembly, and image receptor.

The X-ray Tube

The design of a mammographic x-ray tube is unique in several ways. These special x-ray tubes are physically smaller, overall, than those used in general radiography and are designed to produce the low energy x-ray spectrum needed to create a high-contrast image of breast tissue. Mammography tubes are designed to operate at voltage potentials in the range of 20 kVp to 40 kVp. However, relatively high mA's, typically @ 30–100 mA, are required to image dense or malignant breasts. Thus, mammography tubes must have high output ratings (i.e., 8 mR/mAs or greater).

Two designs are commonly used by x-ray tube manufacturers: grounded cathode and grounded anode x-ray tubes. The grounded cathode tube is the most common design because it is simpler to manufacture and therefore cheaper to produce. However, a grounded anode tube is the best design, overall, mainly because it greatly reduces off-focus radiation which can affect image quality. The grounded anode tube is more difficult to manufacture, though, and can cost three times as much as a cathode grounded tube. In either case, the cost of manufacturing mammography x-ray tubes is much higher than for x-ray tubes used in general radiography.

Another consideration with x-ray tubes relates to equipment usage, especially the high number of exposures taken for each patient. In a typical mammographic diagnostic study, 10 or more exposures may be required, depending on the condition of the patient. The x-ray tube must be able to dissipate the excessive heat that is generated during a mammography examination. Consequently, most mammography x-ray tubes are designed with a relatively large housing in relation to its insert, which is surrounded by insulating oil. The large tube housing, used in conjunction with a vented hood surrounding the x-ray tube, and a relatively high-volume blower (box fan) all help to dissipate the heat generated during the examination.

As stated earlier, a single high voltage cable is frequently used to carry the kilovoltage to the x-ray tube. The ALDEN cable, originally designed for use in the power supplies for CRT-type display monitors, plugs directly into the anode end of the x-ray tube housing. The ALDEN cable conducts both the anode and cathode voltages. With this single cable design, a second cable is needed to supply power to the filament and tube safety circuits. This second, low voltage cable runs from the high voltage transformer to a separate connector found on the x-ray tube housing. By having the power connectors located at the anode end of the housing, the tube glass insert can be positioned within the housing so that the exit port is closest to the patient. The port should be as close as possible to the patient's chest wall so that the entire breast can be imaged.

Another important feature of mammographic x-ray tubes is the use of a very small focal spot size, which is required to image the micro-calcifications and fibrotic strands in the breast. Common focuses used in mammography range from 0.1 mm to 0.3 mm. These focuses are very small in comparison to those used in general radiography, which usually range from 0.6 mm to 1.5 mm.

The target is also specially designed to produce an x-ray beam consisting mostly of low-energy x-ray radiation. Though some x-ray tube manufacturers use a double surfaced anode, using a combination of molybdenum and rhodium in their design, most targets are primarily made of molybdenum, which produces a higher portion of low energy x-ray radiation in the 17.5-19.6 KeV range. Molybdenum targets, when used in combination with the correct filters, allow for effective control over the radiation spectrum required for optimum breast imaging. Even though molybdenum is optimum for mammography, it has a lower melting point which will cause the target to erode over time. As with all x-ray tubes, the electrons colliding with the target produce a heel effect. Since the thickness of the breast is greatest at the chest wall, the target should always be oriented to the nipple end of the patient.

The window or port of a mammographic x-ray tube is also made of a special material that allows only soft x-ray radiation to pass through to the patient. The lower-energy radiation will be differentially absorbed within the soft tissue of the breast providing a high contrast image. Beryllium windows are commonly used in these x-ray tubes.

The Filter Assembly

For mammography, the lower-energy x-ray beam exiting the port of the x-ray tube must undergo additional filtration to produce a beam of sufficient characteristics that will produce a diagnostic image of the breast. And because of the great variation in breast tissue, one filter is not sufficient to image all types of breast tissue. The tissue can vary significantly due to the age and condition of the patient. For example, the breast of a normal adolescent female will generally contain much less fatty tissue than that of mature female. Even more, a breast with abundant fibrotic tissue or one with an implant will require different levels of radiation to obtain a satisfactory image.

Because of the variation in breast tissue, the x-ray beam is further modified for each patient to obtain an optimum image. In mammography, the quality of the beam is modified by varying the kVp and, more significantly, by adjusting target/filter combination. Rather than an aluminum filter, which is used for general radiography, most mammography units utilize two different filters to further adjust the beam quality: molybdenum and rhodium filters. Molybdenum filters are used for small to normal density breasts, whereas rhodium filters are used for large or dense breast, especially when higher kVp's are needed. Both filters will suppress the very low-energy components of the x-ray spectrum that do not contribute to the image while reducing higher energy radiation above the *K absorption edge* that is characteristic of each filter. In effect, by using selective filtering only a narrow band of radiation will reach the patient. The low energy beam with the additional filtration applied results in a beam quality with an HVL value that is much lower than that used for general radiography. The HVL required for mammography ranges from 0.3 mm to 0.5 mm of aluminum, vs. 3.0 mm to 5.0 mm of AL used for general radiography.

The filter, as in general radiography, is always positioned as close as possible to the x-ray tube port. However, since two different filters are used, a mechanical means of changing these filters is needed. Most mammography units utilize a motorized filter assembly that allows the operator to change filters from the operator control work station. Most equipment designs provide automatic filter selection based on the technique used. An "auto-filter" mode of operation is preferable since it greatly reduces any chance of operator error.

The Collimator

The collimator on most mammography units is of two common types. Earlier vintage machines utilized a diaphragm assembly. In this design, a diaphragm is precisely matched to the specific image receptor being used. The diaphragm is inserted into a slot located near the x-ray tube port in preparation for the exposure. By using only that diaphragm, the operator is assured that the light and x-ray field will exactly match the image receptor.

Newer units have a motorized collimator assembly. With motorized collimation, each of the four blades of the collimator has a separate drive motor that can be individually adjusted. During calibration, these blades are set to match the size of the image receptor. Motorized collimators are not only convenient but also provide more precise collimation of the radiation field.

The collimator lamp used in mammography is the same as used in general radiography. The high-output, halogen lamp should illuminate the entire exposure field to within two percent of SID and must meet the minimum light output (160 lux minimum/15 foot-candles) required by MQSA standards. The latest designs employ LED technology to illuminate the radiation field. LEDs are preferred due to their much longer life and lower-energy requirements. Halogen lamps will burn out after a period of use and must be replaced. Each time a lamp is replaced, the light field must be aligned and tested for accuracy. Mammography x-ray units have a precise means of adjusting the size and position of the light field. When the lamp has burned out, it should be replaced by a qualified service engineer, only because of the many adjustments that are needed.

A face shield is an important component of the mammographic unit because of the proximity of the patient to the x-ray tube. Usually attached to collimator assembly, the face shield is made of a hardened, lead-lined acrylic. MQSA requires that the face shield be in place during the examination because it greatly helps in reducing the amount of scatter radiation directed towards the patient.

The Compression Assembly

To produce a diagnostic quality image of breast tissue, compression must be used. Breast compression accomplishes several important goals, all of which help improve the image quality of a mammogram. Compression reduces the overall thickness of the breast so that the beam will pass through less tissue, thereby reducing scatter radiation. By reducing the amount of scatter radiation, there is less radiation dosage absorbed by the patient and, in addition, there is an improvement in image contrast. The use of compression also reduces the OID (object to image distance), greatly improving image resolution.

There are numerous other benefits to breast compression as well. When breast compression is used, the healthy tissue will spread more easily than will lesions or masses. As a result, breast compression helps visualize true masses and reduces the likelihood of false identification of lesion. Finally, compression helps reduce patient motion and suppresses arterial pulsations which helps improve image sharpness.

Because of the many advantages of utilizing compression, mammography units provide both manual and motorized tissue compression (Figure 45). Motorized compression is initiated either by a footswitch located at the base of the gantry or, by a switch located on the c-arm. In preparation for an exposure, the technologist will position the patient's breast directly onto the image receptor surface and then lower the compression paddle (motorized compression) down onto the breast to a precompression force level. Next, the technologist will manually compress the breast by turning the compression knob until the desired amount of compression is achieved.

The compression assembly consists of a compression drive, a compression carriage, and a compression paddle. A compression motor drives the compression carriage (with paddle) up and down the c-arm via a chain or belt. Once in position, the motor brake prevents any backlash in the compression carriage. Also, for patient safety, the compression drive includes a clutch assembly, designed to prevent overcompression during manual compression.

The motorized precompression force is adjustable in the range from 15 to 30 pounds of force. For manual compression, the compression clutch will disable the compression drive when a maximum compression of typically 65 pounds is reached. Most units provide a means of indicating the compression height and compression force used during the exposure since these values are used by the radiologist when analyzing the image. Also, the compression assembly usually includes an automatic compression release feature. Here, once the exposure has been completed, the compression paddle retracts automatically, thus aiding patient comfort.

The compression paddle should meet certain guidelines. Each paddle must match the exact size of the image receptor. Since the paddles are interchanged frequently throughout the day, they should be designed for quick and effortless removal and replacement. Most importantly, the paddles should be strong enough to withstand a significant force, yet must not alter the x-ray beam in any way. Consequently, most paddles are made of acrylic. With proper care, these compression paddles could last for many years.

The Image Receptor

The image receptor assembly used in mammography is similar in function to the one used for general radiography, again, modified for breast imaging. The image receptor includes the x-ray grid system, the digital detector, and the automatic exposure control (AEC) circuit. In addition, a magnification table is an integral part of all mammography units.

As stated earlier in this chapter, the x-ray tube and image receptor are physically attached to the c-arm at a fixed SID. The receptor assembly is attached to the bottom or foot end of the c-arm, providing a solid surface on which to position the breast. The receptor surface (or table) must be rigid and free of defects that could cause artifact on the image.

The image receptor assembly houses the x-ray grid and grid drive mechanism. The x-ray grid moves continuously during the exposure so that the image is free of grid lines. For mammography, two special grids are utilized to improve image quality: linear grids and cellular grids. Linear grids are most commonly used by equipment manufacturers. Because of the absorption characteristics of breast tissue and the increase in radiation dose associated with higher grid ratios, linear grids should always have a low grid ratio. Grid ratios of 4:1 or 5:1 (lines per inch) are commonly used in mammography units. Cellular grids, which are also highly effective at reducing scatter radiation at very low kVps are also used.

Historically, the image receptor included the film cassette holder. A film cassette loaded with unexposed film was positioned into the Bucky assembly in preparation of exposure. Once the exposure is taken, the cassette is removed by manually pressing a latch release and taken to a darkroom for processing. Today, digital detectors are used to capture and process the images of the breast. These detectors are like the digital panels used in general radiography but are designed for the standard 24 cm x 30 cm (or 18 cm x 24 cm) formats used in mammography. They are exposed directly, sending the digital information to the gantry and console for further processing.

The X-ray Control/Work Station

The x-ray control (or work station) is always located near the gantry, or may be directly attached to the gantry, so that the technologist will be in direct view of the patient during the exam. The viewing monitor and x-ray control are fixed behind a lead shield which protects the operator from radiation exposure. The x-ray control is similar in design to all other x-ray control units, allowing the operator to select the x-ray exposure technique, the mode of operation, the filter type, and to initiate the exposure sequence. In addition, the patient data is entered via the control console keyboard and, once the exam has been completed the patient information along with images can be stored on a hard drive, burned to a CD, or sent to a server.

VIEWING CONDITIONS

The environmental conditions of the reading room, important for general radiography, are crucial in mammography. Ideal viewing conditions are essential for the proper diagnoses of mammograms, so that the soft tissue can be carefully evaluated. Also, these viewing conditions should be consistent everywhere, so an imaged viewed at one facility will appear the same when viewed at a different imaging center. Radiologists must rely on this consistency. Consequently, specific guidelines have been established and are enforced in mammography to ensure optimum viewing conditions everywhere.

In the past, when film was used, the images of the breast were viewed on a backlit veiwbox. The light output requirement of a veiwbox for mammograms was much higher than the requirements for general radiography, 2000–3000 cd/m^2 vs. 1400 cd/m^2 for general radiography. Images were viewed in a darkened room, and the radiologist would routinely mask the area immediately around the film to block out light that could distract or interfere with a diagnosis. Furthermore, a high intensity (20,000 cd/m2) spotlight was used by radiologist to aid in the visualization of the fine details in areas of higher density. A magnifying lens of at least two times magnification, an MQSA requirement, was also used in the image evaluation.

Today, all the above viewing techniques are easily accommodated with a high-resolution monitor, 3–5 megapixels or more, for example.

The digital image is adjusted for optimum viewing by use of window and level adjustments, and by use of software tools, such as magnification tool, resizing and collimation tools.

INSTALLATION OF MAMMOGRAPHY EQUIPMENT

The installation of a mammography unit is much simplified over that of general radiographic equipment. The stand-alone design eliminates the elaborate cable runs and most of the alignment procedures needed for radiography. For installation, the assembler will locate the unit within the mammographic examination room as specified by the room drawing and secure it to the floor. A dedicated power line is connected directly to the power circuits in the gantry, and one or more interconnect cables are run between the gantry and control console.

Most units are calibrated at the factory for the specific x-ray tube installed, and the units are fully tested. A mammography unit is essentially ready for use when it arrives. Usually a functional test is all that is required to verify proper operation and to ensure that the unit was not damaged in any way during shipment. During the install the service engineer should always verify all calibrations, especially the mA calibrations and compression adjustments. Finally, image quality checks are performed and recorded.

QUALITY ASSURANCE IN MAMMOGRAPHY

Before proceeding with calibrations, it is important to understand the source of the calibration standards. In the United States, all aspects of mammography are prescribed by the Mammography Quality Standards Act (MQSA). MQSA sets guidelines for all aspects of mammography, including standards for radiation producing equipment, image quality, viewing conditions of the reading room, and even for record keeping. These guidelines, enforced by the FDA (Food and Drug Administration), were created to ensure that patients receive consistent quality care at all mammography centers. To operate legally, every mammography facility in the USA must be accredited by the American College of Radiology, or ACR. Designated by the FDA, the ACR establishes standards and practices that are used in mammography. In addition, each mammography center is required to perform comprehensive quality assurance (QA) testing of the entire mammographic system.

Mammography units are checked weekly using a special mammography phantom. The phantom used for mammography must be approved by the ACR. A typical ACR phantom, made of acrylic, contains a wax insert with fibers, specks, and masses embedded in the wax. The phantom must simulate a 4.2 cm compressed breast and the phantom image should reveal at least four fibers, three masses, and four specs. MQSA/ACR guidelines for phantoms can be found at each facility and are available on the internet.

Equipment calibrations are also set by the MQSA. When new equipment is installed, the service engineer must follow the established guidelines for calibration accuracy. Once a unit is installed, it must be thoroughly tested by an independent radiation physicist who will ensure the all guidelines and standards are met.

PREVENTIVE MAINTENANCE AND CALIBRATION

Mammography units are calibrated to meet all the manufacturer's specifications, which must also comply with MQSA guidelines. Mammography systems should be inspected and calibrated at least two times per year. When servicing equipment, the engineer can follow the general guidelines for preventive maintenance and calibration that are used for radiographic equipment. Specifically, the service engineer should clean and inspect the mechanical assemblies, verifying correct operation. Also, the x-ray generator can be calibrated using the principles described earlier in this book.

Additionally, the compression assembly must be tested and adjusted to achieve safe and effective compression forces and to display the correct compression height. The collimator assembly requires cleaning since dust tends to accumulate in this area. Collimator shutter adjustments should be verified and documented on a test image. Finally, the engineer must perform image evaluation tests, using flat field phantoms as well as the mammography phantom tests.

FAILURES WITH MAMMOGRAPHY UNITS

Mammography equipment will fail in ways similar to and with the same frequency as general radiographic equipment. The difference with mammography service lies in the servicing approach. The main purpose of a mammography examination is cancer screening. Patients who arrive for examination are often anxious, worried, intimidated, and, at the very least, uncomfortable. The service professional should be conscious of the sensitive nature of mammography service and should always use discretion when on service calls. A good practice when arriving for service is to register at the reception area and then remain in a designated waiting area until permission is given to enter the mammography suite. The engineer's service tools and test equipment should remain outside of the imaging center as well, since their presence could be a distraction to the patients. As always, a professional appearance and common courtesy go a long way.

When servicing mammography equipment, the engineer can utilize the troubleshooting practices outlined earlier in this book. In fact, experience in general radiographic equipment service is of great advantage when tackling the service issues specific to mammography. Many failures occur with mechanical assemblies such as electromagnetic locks, motor drives, control switches, and other common x-ray components. Failures in these areas can be corrected using general repair skills. Below we will concentrate on the failures that are unique to mammography equipment, detailing ways to isolate their causes.

Mechanical failures with mammography units commonly occur in the compression drive assembly, filter assembly, and the gantry drive. Because of the amount of force used during compression, the major components of the compression drive tend to fail over time. Specifically, drive chains will break, gears become worn, and the clutch and drive motor will eventually fail. The compression paddle, which is removed and then reinserted for each case, will require repair or replacement after a period of use. Also, if excessive compression is applied repeatedly to the test phantom, cracks will form in the paddle, creating artifacts on the images. The c-arm is rotated repeatedly throughout the day. Parts can loosen over time in the rotation drive, and cables can become dislodged. The grid located in the image receptor should also be checked for smooth and quiet movement.

By far, most mammography service calls are related to a loss of image quality; the most common of these calls deals specifically with image noise and image artifacts. As with DR flat panels, performing routine calibrations can remove minor defects and help to maintain good image quality.

Once service has been completed on the unit, the engineer should always take one more phantom shot to verify proper operation of the entire system. Test images should be saved at the site along with the service report to document calibrations.

Chapter XIII

ESTABLISHING AND MAINTAINING GOOD CUSTOMER RELATIONS

A book on x-ray servicing would not be complete without some mention of the relationship between the service engineer and the customer: the equipment owner or end user. After all, a main goal of a service organization is customer satisfaction. Hopefully, if the customer is happy with the service being provided, that customer will continue using that service. The responsibility for establishing and maintaining good customer relations lies on all members of an organization. This is especially true for the sales and service staff members since they usually will have the most contact with the customer.

With a new equipment purchase, the customer will deal almost exclusively with a member of the sales staff of the equipment dealer. The salesperson will introduce the customer to the product, take the customer to facilities to see the equipment and to view its operation, negotiate the sale of the equipment, and meet with the customer as often as necessary to coordinate the installation of the equipment. Only occasionally, when his or her technical expertise is required, will it be necessary for the service engineer to meet with the customer.

However, once the sales agreement has been signed and the preliminary stages of the installation are well underway, the salesperson will begin to play a secondary role in dealing with the customer. Now, the service engineer becomes the more visible representative of the equipment dealer, and must therefore be prepared to attend to other customer needs as they begin to surface. Furthermore, when the installation is completed, the x-ray service engineer may well become the only member of the x-ray equipment dealer (or service provider) who will regularly interact with the customer. The responsibility for customer satisfaction will, therefore, depend solely on the service engineer.

Thus, expertise in equipment servicing alone will not suffice when working in this field. The engineer must, in addition, possess the social skills required to establish and maintain a good relationship with the customer. Indeed, the electronic "wizard" who can fix any x-ray equipment on the planet cannot survive in the servicing field if he or she cannot at the same time deal effectively with people.

Good customer relations benefits both the customer and the service provider as well. Usually, the satisfied customer will opt for future service with that provider, which is financially beneficial to that provider. Conversely, a bad relationship resulting from the inappropriate actions of the service engineer can be very costly to the service provider.

For example, a service engineer may inadvertently so anger a staff member of the facility that the customer will respond by refusing to allow that individual to perform any further service on their equipment. Here, the service company will then normally comply with the customer's refusal and send another engineer to that site. Such an error on the part of the engineer not only severely encumbers the service capabilities of the service organization, but also reflects poorly on the organization, as well as its personnel.

Furthermore, many service calls are not at all related to equipment failure. There are some customers who, unfortunately, may have a negative impression of the brand of equipment, regardless of its performance. This negative bias towards the equipment may have resulted from problems that the staff member had experienced at some time in the past at another institution, or it could be that a radiologist, for whatever reason, simply may not like the design of the equipment.

Whether preconceived or not, the engineer must attempt to understand why the customer dislikes the equipment and then must remedy the situation. Sometimes, minor aesthetic changes made to the equipment can resolve this type of problem. Other solutions may involve modifications to the equipment (preapproved by the equipment manufacturer, of course) to allow the equipment to operate to the customer's expectations. Here, the service engineer must be resourceful when resolving this type of customer problem. In this case the service engineer is "fixing the customer."

It is an undeniable fact that good customer relation skills can lead to the success of a service organization. This is especially true, given the fact that most x-ray units have very similar performance characteristics. Accordingly, the performance of the service organization, especially that of the service engineer, can make the difference as to which equipment or service a customer will opt for in the future.

Because of the immense growth of personnel within this field, there are any number of service engineers available to fix x-ray equipment. In such a competitive field, it is vital for a service organization to find ways to maintain a competitive edge. Good customer skills can help maintain that edge. To achieve this goal, many x-ray dealers are now investing time and money into educating their staff on how to improve the customer relation skills.

Although a complete course in customer relation skills may be a bit excessive for our purposes here, the engineer should be familiar with those factors that can effectively promote good customer relations. It has been the experience of the author that if the service engineer adheres to the common-sense practices listed below, he or she will automatically promote and maintain good relations with the customer.

APPEARANCE

The service engineer should always dress professionally when servicing x-ray equipment. It is a simple fact that appearance makes a strong impression on the customer. A well-dressed service engineer projects a positive image for himself or herself and the organization he or she represents. Proper dress for service engineers might well consist of a dress shirt or polo shirt with a company logo, and dark slacks, or a slight variation.

Because of the very nature of x-ray service, it is often difficult to maintain a clean appearance throughout the day. During a typical day, the engineer will handle grease, oil, and other fluids that can stain his or her clothing. Fortunately, inexpensive clothing is available today that is made of very durable, wrinkle free, wash and wear fabrics. The engineer can dress well without incurring a great expense for clothing and the high cost of dry cleaning.

ATTITUDE

The service engineer is in this business to solve problems–not to cause or enhance them. In most cases, the engineer is called to the site because the equipment has failed in some way. Consequently, he or she will regularly deal with people who are upset, frustrated, and even angry. If not prepared for these often-tense situations, the engineer can easily become discouraged, or become negative.

When equipment breaks down, it may completely disrupt the functions of the facility. This stressful environment requires a pleasant and calming demeanor on the part of the engineer to diffuse an otherwise explosive situation. By having a positive attitude when approaching a service call, the engineer will solve the problem much more easily and will leave behind a much happier customer.

Most causes for the strong emotions of the customer can, however, be easily resolved once the engineer begins to address the problem. If the engineer is positive in outlook, pleasant in manner, and greets the customer with a smile, he or she will achieve much better results. A positive attitude communicates that the problem is probably not so severe after all, and the engineer will be happy to take care of it. Being pleasant and amiable is a plus for that engineer, as well as the service provider.

RELIABILITY

The customer must be able to count on the service engineer for prompt service. If the engineer schedules service with a customer, he or she should promptly arrive at the prearranged time. There is no acceptable excuse for being late and making a customer wait. This action communicates only that the customer is not important. The engineer should also be prompt when returning phone calls and should make sure that any promises or commitments are kept, as well.

COMPETENCE

The engineer must be confident in his or her ability to resolve x-ray failures and must demonstrate to the customer that he or she can do the work. Usually, it only takes one or two service calls to gain the customer's confidence (or lack of it). Oftentimes, a service engineer, while on a service call, will save the customer great expense by detecting (and fixing), in addition to the original failure, an annoying problem that has been intermittently occurring with the equipment. As a result, he or she will have won the confidence, as well as the goodwill of the customer.

If an engineer is unable to resolve an x-ray problem, the customer will be most appreciative if he or she is honest about it. No one person can repair every problem that may occur with x-ray equipment. If the engineer must call for assistance, the customer will simply note that the engineer did whatever it took to get the equipment operational.

COMMUNICATION

The service engineer must speak clearly when conveying information about a service problem to the customer, for the image he or she projects is that of the service organization. In addition, the engineer must carefully describe (in laymen's terms) a technical failure and then explain how he or she repaired it. By doing so, the engineer shows that he or she respects the customer's intelligence and desires to keep him abreast of the situation.

To do this, the engineer must convert highly technical details on equipment failures into terms that the customer can easily understand. It is often difficult to do this, given the complexity of electronics and equipment designs. If, however, the engineer can readily explain equipment failures (and their solutions) in relatively simple terms, the customer will feel more confident and comfortable with the service that is being performed.

An important part of good communication involves listening. The service engineer must listen carefully to what the customer may be trying to say and should always try to respond in the customer's best interest. "Best interest" might even entail offering the customer less expensive options or different solutions to a problem. The engineer who insists on repairing equipment, callously disregarding the cost to the customer, will soon be out of business.

It is very easy to underestimate the customer's ability to communicate and understand technical information. Engineers will often arrogantly ignore the customer's input on the service problem if they feel they already know what the problem is. Many customer relation problems result when the engineer repairs something that was not what the customer originally meant to be addressed, because that customer simply lacked the vocabulary or expertise needed to explain his or her problem thoroughly.

If the cause of the problem is found to be due to operator error, the engineer should in no way lay the blame on any individual for causing the failure. If a device has been used in the wrong way, its use may never have been properly demonstrated to the technician concerned. Here, the engineer should then demonstrate the correct use of the equipment to eliminate similar service calls in the future. If the engineer decides that the person at fault will suffer consequences from a mistake (i.e., by being reprimanded by a superior), the engineer might then suggest, for example, that he or she has "discovered a loose connection that may have caused the equipment problem and easily repaired it."

The author, here, is not advocating the practice of lying to the customer. However, as with every daily life interactions, a little white lie (as in the case above) may greatly aid in improving relations. The technician who made the mistake will more than likely recognize his or her error and appreciate the engineer's discretion. The engineer has now made at least one fast friend on that staff.

Clearly, it benefits absolutely no one to point a finger at an individual and will almost always result in a distrust of the engineer by many of the personnel at the hospital. Remembering that human beings do make mistakes, and that x-ray technicians are focused mainly on the patients, who may be very sick or uncooperative, the temptation to make accusations will seldom arise. It should go without saying that the service engineer also makes mistakes.

ADDITIONAL SUGGESTIONS FOR IMPROVING CUSTOMER RELATIONS

- Listen carefully to the customer and address each concern individually. The best practice is to interact directly with either the chief technologist or the radiologist of that department.

- Try to offer alternative, less expensive solutions to problems with equipment.
- Do not "nickel and dime" a customer to death. Minor services should be provided at no cost to an established, loyal customer.
- Always remember to focus on patient and staff safety when dealing with any service issue.
- Make courtesy calls to customers even when equipment is functioning properly. Such a visit demonstrates a genuine concern for the customer and will help maintain good customer relations.
- Clean equipment thoroughly after performing service. Any marks left on the equipment reflects negatively on the service engineer.

EPILOGUE

BECOMING A SENIOR ENGINEER

To service medical instrumentation effectively, a service technician should possess skills in many areas of expertise. Service "techs" require good mechanical skills, must be experienced in troubleshooting both analog and digital circuits, and should have knowledge of computer operation and repair. In addition, all service professionals working in healthcare should possess a good working knowledge of human anatomy and physiology, which will help them to better understand the design and application of medical equipment. Proficiency in these disciplines is essential because the equipment being serviced will be used to treat or diagnose patients, and their lives could depend on equipment accuracy.

Moreover, technical expertise is especially important when servicing x-ray equipment which involves both dangerous voltages and potentially hazardous radiation levels. An incorrect calibration or adjustment could cause serious injury to the engineer, patient, or staff, not to mention the damage that could result to the very costly equipment. Service personnel new to this field require extensive training before attempting to tackle the many challenges associated with servicing x-ray equipment.

It can take many years for service engineers to gain the expertise required to work proficiently in this field. The engineer must perform countless calibrations and repairs on many different brands of equipment as he or she advances in the field. Only after experiencing many of the common types of failures occurring with radiographic equipment will he or she be able to diagnose and repair these failures efficiently.

The fact is that experienced engineers troubleshoot and repair equipment failures quickly and reliably, and when they leave the equipment site after a service call, they are usually confident that the unit will perform reliably, and to manufacturer's standards. They have become seasoned engineers. These experts have earned the respect of their supervisors, as well as their peers, and have become an asset to their organization. They have reached the level of "senior service engineer."

All service engineers would like to provide the best service possible, but realize that they must go through a learning curve which is a difficult and not always pleasant experience. This chapter will describe the various phases of an engineer's training and provide tips on how to get the most out of each phase while he or she is learning the trade. Next, servicing techniques are discussed which will help the engineer to develop skills so that he or she can perform repairs more reliably. The goal of this chapter is to help new engineers to attain the skill level of a "Senior Imaging Specialist" as quickly as possible.

THE LEARNING PHASE

Anyone seriously interested in the field of x-ray service should first begin by learning as much as possible by reading everything he or she can on this subject. They should attend a school that provides training in the classroom as well as instruction in a laboratory setting. Once this education phase is completed, he or she must work in the field for some time serving an internship phase to gain the experience and confidence required for this job. It is during the internship that the engineer truly begins to learn the ins and outs of the trade. Usually working under the guidance of a senior engineer, the intern will put to test the practices learned in the classroom. This ideal setting takes much of the pressure off the intern so that the focus can remain on the equipment and servicing practices. As mistakes are made, the "mentor" can convert the error into a learning experience that will benefit the intern. The fact is that we often learn best from our mistakes: the embarrassment and frustration serve as a mental cue on future service calls. The key for newer service personnel is to take advantage of this internship phase, learning as much as possible and progressing through this necessary but awkward stage as quickly as possible.

At some point during this training, however, the intern must go it alone. There is only so much a person can learn from observing others, and the time comes when the engineer will perform service on his or her own. This important period of training is also the most difficult. Though it is vital that the engineer begin working independently, the concept of training while on the job can be very intimidating. After all, customers are paying for service and expect a "professional" to do the work. Engineers often comment on the frustration associated with these initial service calls because they sincerely want to satisfy the customer, yet they do not have the experience to perform their duties with confidence. The plain truth is that OJT (On-the-Job Training), commonly used in many specialized fields, is an effective means of training. During this training phase, it helps for the engineer to be mindful of the fact that he or she is not the only one who has gone through this phase. Everyone was a novice at one time.

Good or bad, the OJT phase is the way most engineers develop their skills. As a rule, the most basic of service problems are assigned to the new engineer, and as experience is gained, the service calls will increase in complexity. As a representative of the service organization, the engineer should always strive to provide the best quality service. When confronted with an equipment failure not experienced before, the engineer should utilize all the resources that are available, such as consulting the operator and service manuals, calling coworkers, or even contacting the equipment manufacturer for assistance, if necessary. Many engineers ask members of the hospital staff to demonstrate equipment operation to learn about an equipment failure–a very good approach. The point is to do whatever it takes to pin down the source of the problem and effect a repair. By taking an active approach, the engineer will quickly build the valuable experience needed for this job.

Every engineer must progress through each phase of the learning curve. But there are ways for an engineer to expedite this process and greatly shorten the time spent learning the trade. Included below are tips to aid the engineer to move quickly through the learning phases.

Understanding X-ray Theory

The first hurdle to overcome when beginning a career in the x-ray servicing field is to learn and understand fully the fundamentals of x-ray theory. Specifically, the engineer must know what x-ray radiation is, how it is produced, and how it interacts with matter to create the images used to diagnose medical problems. Possessing an in-depth knowledge of x-ray theory will greatly help when troubleshooting imaging problems. The engineer should focus on the effects that scatter radiation has on the final image. Also, with an awareness of the harmful effects of scatter radiation, he or she will be able to work confidently and safely around radiation producing equipment.

Learning Equipment Design

The newly hired service engineer should next concentrate on learning x-ray equipment design. He or she should know precisely how each device found in the x-ray room contributes to the process of creating and modifying the x-ray beam. The specific devices of the x-ray system, detailed in an earlier chapter, include the x-ray generator, the x-ray tube and tube support, the collimator, image receptor, wall receptor, and the radiographic table. Although designs may vary among the manufacturers, the function of each device remains the same.

For example, each type of x-ray generator has a distinctive output waveform, and there is a significant difference in the image formed from a single-phase generator and one from a high frequency unit. Also, the effects of different x-ray tube types are striking. The engineer should know the consequences of using different target angles and filament sizes and should know the best application for each tube type.

Once x-ray radiation exits the x-ray tube port, anything lying directly in the path of the beam will alter its intensity and overall quality. The components of the collimator assembly, for instance, can attenuate, concentrate, soften, or totally block the x-ray beam. Many different types of x-ray grids are available that can drastically affect image quality. An engineer who knows the inventory of grid types can suggest alternatives to the customer, when asked. By doing so, he or she will communicate expertise and professionalism to that customer.

Learning Equipment Operation

Understanding equipment design and function is one thing, knowing how to operate equipment is another. Service professionals must take the time to learn equipment operation. In fact, a service engineer should know how to operate the equipment even before he or she can attempt a repair. X-ray equipment designs vary among manufacturers, and each design incorporates unique ways of accomplishing tasks such as setting technique factors, modes of operation, and selecting types of receptors. In addition, each unit has its own characteristic audible sounds and visual indications that identify the exposure sequence and indicate equipment errors. Specifically, the engineer should note the distinctive sounds of the rotating anode of an x-ray tube, the duration of the prep cycle, and the sounds and indications of the x-ray generator during a normal exposure. These audible clues can be used when troubleshooting an equipment failure.

Initially, the best way to learn equipment operation is to observe the equipment while it is in use with patients during examinations. By doing so, the engineer will see the typical movements of the radiographic table and tube support during a routine x-ray procedure. Furthermore, he or she will see how an x-ray examination is performed, noting the sequence of events leading to the exposure.

For in-house engineers, observing patient exams is an easy task. He or she can simply ask the chief technologist or the attending radiologist for permission to observe a few x-ray studies. In most cases the staff will be more than happy to show you their work. They may even point out a few things about the equipment that they like (or dislike). Almost certainly, the staff will appreciate your interest and will want to help you to better understand the specific nuances and quirks of the x-ray system.

Service engineers working for independent service organizations (ISOs) or original equipment manufacturers (OEMs) may have more difficulty getting into rooms for observation since they are not employed by the hospital and must account for their time. Representatives of "third-party" organizations are billing for their time and, in most cases, cannot afford the luxury of remaining at one site for very long. Before performing service, the field service engineers can ask the staff for permission to observe an examination "to learn clues about the failure." Also, the field engineer can follow up on a repair by observing an examination of a patient immediately after completing a repair to "ensure that the unit is working to specifications." This practice also communicates professionalism and helps promote customer relations.

During this observation time, the service engineer will see exactly how the equipment is used on patients, noting the sequence of events in common x-ray examinations and learning how different technologists perform the same examination. This information will prove very helpful when troubleshooting equipment failures and will greatly save time on future service calls.

The next step when learning equipment operation relates to actual hands-on experience. The engineer should operate the equipment without the help of others until he or she feels comfortable with its operation. A good practice is to run through the process of setting up for an exam, programming the x-ray control, positioning the x-ray tube, and, ultimately, taking an exposure. In fact, all modes of operation should be tested. The engineer should expand this course of investigation, learning the operation of other equipment found in the radiology department. Specifically, the service person should learn the various nomenclatures used by different manufacturers, noting the variety of symbols and indicators that are used. At some point, the equipment operation will become second nature to the engineer and when called for service, he or she can speak intelligently about the equipment and can even demonstrate its operation with confidence.

SERVICING NEW EQUIPMENT

When confronted with new or unfamiliar equipment, the engineer can begin using the general troubleshooting skills outlined earlier in this book. When questions arise, ask the staff for help. The hospital staff may realize that an engineer is unfamiliar with their equipment and will be more than glad to help so that they can get their unit up and running. The first repair, no matter what it is, will be the most difficult one that an engineer will make. If an error was made in the troubleshooting process or in the repair itself, a return service call, or service recall, will remedy the situation. Again, the mistake will serve as a memory aid for future service calls.

The second service call on a similar failure will be much easier, but, still, the engineer may not be completely comfortable with the repair. The exact sequence of the repair procedure may not have been memorized, for example, or the engineer may not have remembered to take along the parts needed for the repair. The engineer may even have to place a phone call to the OEM for technical support, or ask a colleague for help. However, the third and fourth service calls on a similar equipment failure should be easily fixed. The engineer now has become an old pro, and in the future, he or she will be the one giving technical advice to colleagues.

THE GOOD REPAIR

When attempting to repair equipment, the engineer should strive to develop a specific and orderly routine that in time will become second nature to that engineer. Once perfected, that routine should be used with every repair. In this manner, the engineer will automatically create a system of inherent checks and balances that will ensure that equipment is repaired properly, thus reducing the chance of errors.

First, when disassembling components, the engineer should arrange the parts on a surface (e.g., table or floor) that is free from clutter so that there will be no chance of misplacing or losing the parts. As each part is removed from the assembly, it should be placed in order on the table maintaining the exact spatial relationship so that it will be much easier to reassemble. Using a clock as illustration, the top cover to an assembly is placed at twelve o'clock, bottom cover at six o'clock, the left cover at nine o'clock, and so on. All screws, washers, spacers, and gaskets are placed on the table maintaining their exact relationship. By matching the exact spatial orientation of the parts, the engineer can reassemble them more confidently and more quickly. This practice works well with parts that are very similar in appearance. The author has used the above technique successfully for over 30 years. Today, in addition to this practice, most service engineers use their cell phones to document the layout of an intricate assembly, or to make a record of any special wiring. A quick photo will ensure that the parts will go back in the way they came out.

Another good habit is to place cover screws or other similar hardware in a tray or small container so that they will not get knocked around or lost. If a work surface is not available, a good practice for the engineer is to label the parts to avoid any confusion. The few extra steps taken here will reduce the chance of error during reassembly.

When the failing component is replaced, it should be tested thoroughly. The engineer should watch for an obvious change in equipment performance with the new components in place: there is no gray area here. In fact, if there is any question at all in the engineer's mind that the original symptom may still exist (even intermittently), the engineer should begin looking elsewhere for the cause of the problem. With x-ray equipment, there could be multiple sources for a given problem, and the engineer must investigate all the possible causes of the failure. A rule of thumb is that if not completely confident with the repair, the engineer can expect to return a second time to repair the same problem.

Once the unit is completely reassembled and all covers are in place, the engineer should perform a functional test of the equipment. As stated in the troubleshooting chapter (Chapter IX), subassemblies and wire harnesses are packed closely together within the equipment cabinets, a drawback to the compact design of x-ray equipment. It is common in x-ray servicing to have equipment develop symptoms of a failure once the equipment covers are back in place–wires get crimped and connectors can become dislodged. It is therefore recommended that the engineer test all modes of operation before leaving the site. An even better practice is to invite a staff member to test the equipment and verify its operation.

RECORD KEEPING

A practice that will guarantee quick advancement for new engineers relates to documentation. Good record keeping is an organizational practice that has proven necessary in many professions. Most seasoned engineers will take detailed notes on specific equipment failures that he or she has experienced and will document the information gleaned from other valuable sources such as from coworkers, technical articles and books, and from course instructors. In fact, the best engineers will maintain a service log containing a history of specific types of service calls and their associated resolution. These engineers will also document unique calibration procedures that are difficult to perform and will record any unusual test waveforms that he or she has encountered.

The simple fact is that the human mind cannot possibly retain every detail of the failures occurring with so many types of equipment. Furthermore, when just starting out, there is simply too much information for the engineer to digest. The engineer who documents the various equipment problems that he or she encounters over the years will be way ahead of the game. The notes can be studied or used as a reference on future service calls.

THE EXTRA EFFORT

When out on a service call, the main goal for the engineer is to get the equipment back up and running as quickly as possible. While performing the repair, however, he or she may notice other minor problems with equipment in the radiographic room. The technologist or staff member may even point out an annoying quirk with the equipment. These minor problems are often tolerated, but the staff will not call service–just to save money. Here is a perfect opportunity for the senior engineer to be proactive and correct the issue.

The engineer can perform small acts that will make a huge difference in the staff's perception of the service performance. Lubricating a noisy mechanical assembly, for example, or replacing missing hardware or burned-out indicator lamps are actions that can be performed with little effort. Also, the engineer can clean or adjust switches so that they snap into position when operated. By performing this additional service, not only is the failure corrected (i.e., the original reason for the service call), but the engineer has eliminated an annoyance that had been bothering the radiology staff for some time. Most top-notch engineers perform these small tasks without mentioning it to the staff. The overall impression left is that the equipment just seems to be working much better after that engineer has been there. The extra effort taken by the service professional will truly pay off in the long run.

Furthermore, the additional service performed may even have prevented a future service call. True, every service organization must make money to stay in business, and major service calls are expected from time to time. However, it is the little nagging service calls that often create a negative view of the equipment, or the service engineer, or both. Also, it is not always a good thing to have an engineer present at the site on a regular basis. The customer may wonder why the engineer is always working on the equipment. Frequent visits often reflect poorly on the engineer as well as on the equipment which may have been purchased from that service engineer's company.

In this author's view, it is more beneficial to make minor repairs while on a service call, rather than having to return to the site. There is another benefit, as well: happy customers will tell others of their experience and thus promote more business for the engineer and his or her service organization.

SUMMARY

It takes time to learn the skills needed to repair radiographic equipment, and given enough time, many students can learn to become good service engineers. However, engineers who want to advance quickly and excel in this field must demonstrate initiative early on and take an active approach to servicing. If the engineer adheres to the guidelines outlined in *X-ray Repair*, he or she will remain on the fast track and soon become a senior engineer–and the goal of this book will have been achieved.

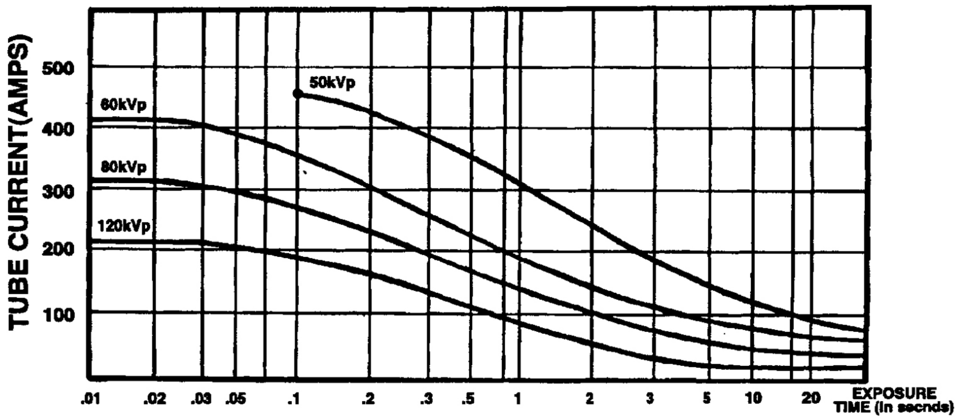
APPENDICES

APPENDIX A

MEASURED kVp	MINIMUM REQUIRED HVL (in millimeters of aluminum)
30	.3
40	.5
50	1.2
60	1.3
70	1.5
80	2.3
90	2.5
100	2.7
110	3.0
120	3.2
130	3.5

Figure 46. HVL Chart.

APPENDIX B



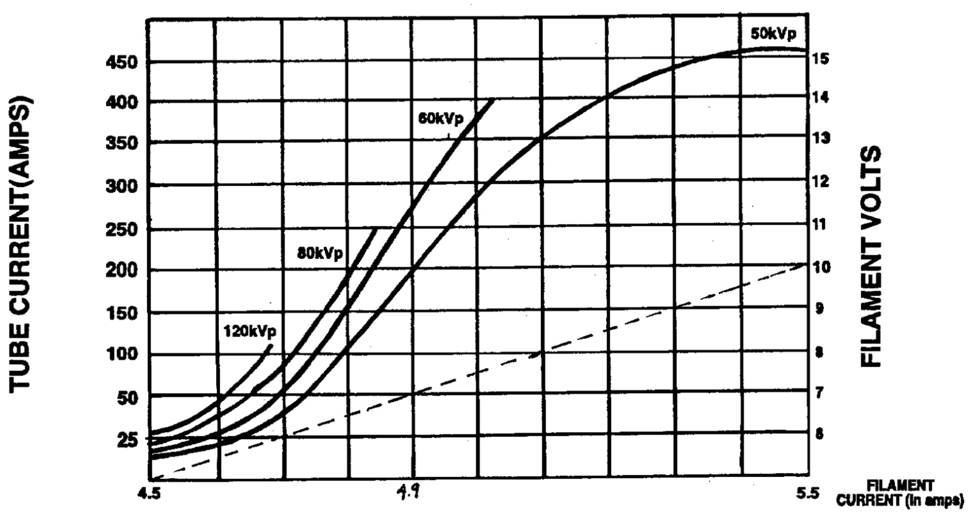


Figure 47. Sample x-ray tube rating charts. (Top): At a setting of 80 kVp, 300 mA, the maximum allowable exposure time is 0.05 seconds. Also, notice that at 50 kVp an emission limit is reached. Therefore, the maximum mA obtainable for this tube is 460 mA at 50 kVp. (Bottom): Note the emission limit at 50 kVp is also graphically represented on the filament emission chart. Also, at 50 kVp we see that 4.9 amps of filament current is required to achieve 200 mA. The dotted line in the chart represents the voltage/current relationship of the filament wire. Specifically, if 10 VAC is applied to the filament wire, the actual measure filament current would be 5.5 amps.

APPENDIX C

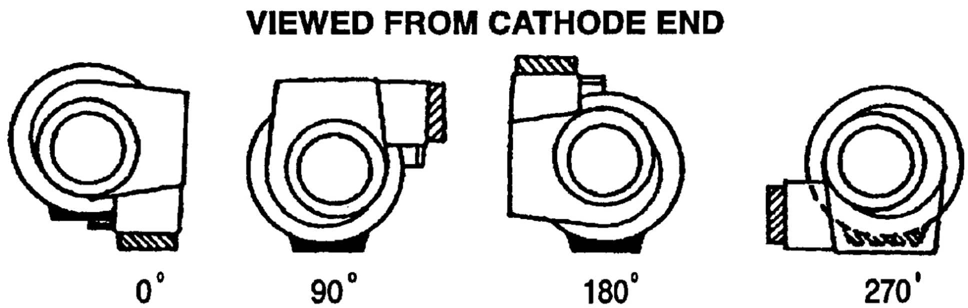


Figure 48. Horn angle designation for x-ray tube housing.

APPENDIX D

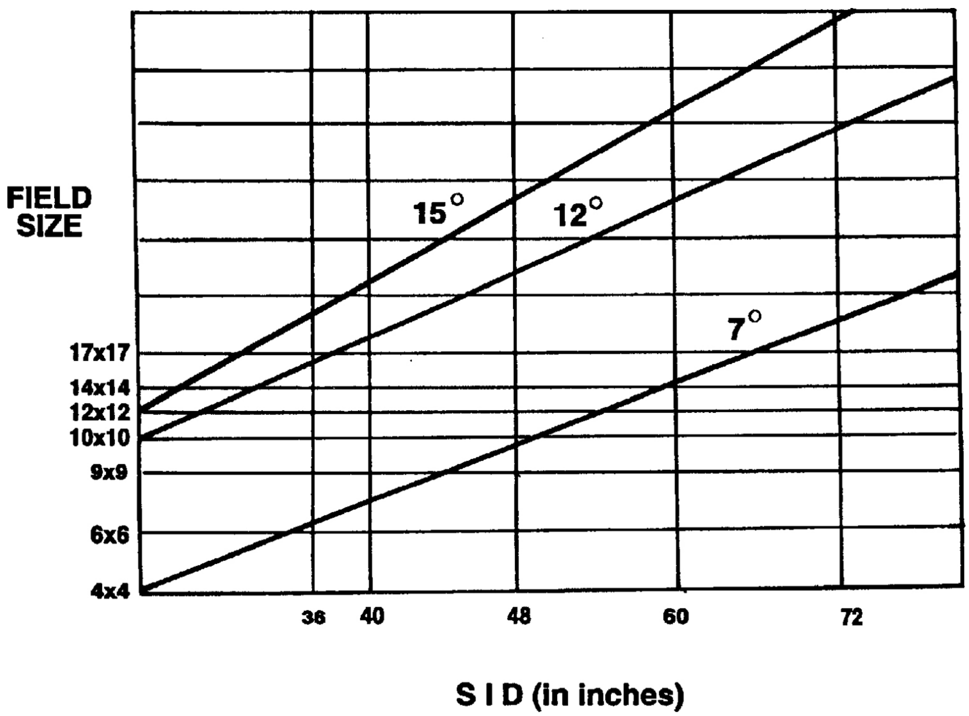
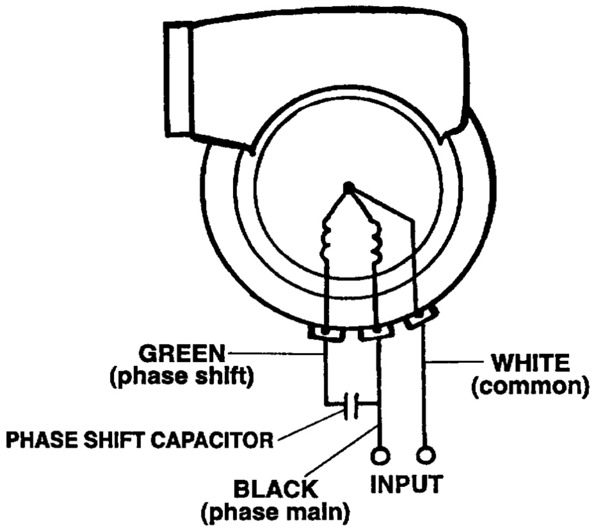


Figure 49. X-ray field coverage for various target angles. Note that a minimum of 40 inches SID is required to achieve 17 inch image coverage with a 12 degree target.

APPENDIX E



STATOR TYPE	IMPEDANCES (Typical) Black - White	Green - White
"R" Type (Standard)	16	50
"Q" Type (Low Impedance)	9	16
"E" Type (Balanced)	23	23

Figure 50. Common x-ray tube stator winding impedances.

APPENDIX F

TOOLS AND TEST EQUIPMENT

Certain specialized tools and test equipment are needed to service x-ray equipment properly. Besides the standard tool kit used for servicing general electronic devices, additional equipment is required for moving and installing radiographic equipment. For x-ray installation and servicing, the following tools and special equipment are needed.

X-ray Service Tool List

1. A Complete Electrician's Tool Kit
2. 3/8″ Electric Drill (light duty)
3. 1/2″ Electric Drill (heavy duty)
4. Hammer Drill (for concrete)
5. Hand truck and furniture dolly (moving equipment)
6. High jack (moving)
7. Johnson Bar (moving)
8. Rollers (moving)
9. Come Along (moving)
10. Electrician's Fish Tape (wire pulling)
11. Socket Set (standard and metric)
12. Open End Wrench Set (standard and metric)
13. 4-foot Spirit Level or precision level (alignment and mounting)
14. Plumb Bob (alignment and mounting)
15. Crow Bar (moving)
16. Hacksaw (just in case)
17. Vacuum Cleaner (installation and PM)

It may not be practical for a service provider such as in-house groups to own all the above equipment because of cost or space limitation; however, the engineer must have access to these tools to provide complete x-ray service. Smaller x-ray companies can rent the moving equipment as needed, and in-house groups can borrow equipment from the plant operations or maintenance departments.

To properly service x-ray equipment, specialized test equipment is also required. The service engineer must be able to measure high voltage and radiation output during calibrations. To properly diagnose problems, the engineer must view the x-ray waveform on an oscilloscope. To check the condition of the x-ray tube and imaging chain, special test phantoms are required. Test equipment needed for x-ray service is listed below. This equipment is mandatory for servicing radiographic equipment.

Test Equipment

1. Digital Volt Meter (DVM)
2. Ammeter (AC clamp type)
3. Digital Storage Oscilloscope (DSO)
4. High Voltage Bleeder or Dynalyzer
5. MAs Meter
6. Dosimeter ("R" output)
7. Non-invasive kVp Meter
8. Light Meter or Photometer (collimator light output)
9. Flat Field Phantom (AEC)
10. Line Pair Phantom (system resolution)
11. Pie Mesh Phantom (system resolution)
12. Lead Star Test Phantom (x-ray tube focus)
13. Laptop Computer (generator programming and troubleshooting)
14. Vibrating Reed Tachometer (anode rotational speed)

APPENDIX G

TOMOGRAPHIC ANGLES vs. SLICE THICKNESS

Angle	Thickness
5°	11.0 mm
10°	6.0 mm
20°	3.0 mm
30°	2.0 mm
40°	1.4 mm
50°	1.1 mm

GLOSSARY

ACR–The American College of Radiology. Establishes standards and practices for mammography.

AL-1100–The type of aluminum alloy used to attenuate the x-ray beams. It is used in beam limiting devices and for testing purposes.

ARTIFACT–Unwanted, additional information located on the imaging medium that is caused by a defect in the imaging chain. Image artifact is a serious problem that can cause misdiagnoses.

BUCKY–A device that contains a reciprocating grid assembly positioned directly in front of the image receptor. Originally called the Potter-Bucky, named after the two inventors: Dr. Hollis E. Potter and Dr. Gustav Bucky.

CASSETTE TRAY–The device that holds the CR cassette or DR panel in position during the exposure. The cassette tray may have cassette size sensing circuitry that is used in conjunction with automatic collimators.

COLLIMATOR–A lead-lined beam limiting device with adjustable shutters that allows the operator to vary the size of the x-ray field. Collimators provide a field lamp for field size indication.

CONE–A lead-lined device that mechanically attaches to the x-ray tube used to limit the x-ray beam. Cones have a fixed field size and do not provide a light localizer.

CONTRAST–The difference in densities between two adjacent areas on the image.

CR–Computed Radiography. Similar to conventional radiography, CR uses a cassette to convert x-ray to light energy but instead of film, an imaging plate (IP) made of photostimulable phosphor is used to record the image. The IP is processed in a CR reader which digitizes the image.

CRAZING–A phenomenon that occurs in x-ray tubes caused by internal arcing. This arcing causes heat expansion inside the tube that results in fractures or cracks of the glass insert. Crazing can be observed by looking directly into the port.

DENSITOMETER–A calibrated device used for measuring film density. Densitometers are used for film processor quality control and during the AEC calibration by service engineers.

DENSITY–The amount of blackening of film measured by a densitometer.

DIAPHRAGMS–A fixed-aperture beam limiting device that attaches directly to the x-ray tube housing. Diaphragms are usually removable.

DR–Digital Radiography. X-ray imaging where radiation directly exposes digital sensors (direct) or radiation exposes a scintillator (indirect) located within a flat panel detector. The detector digitizes the image and sends an electrical signal to a computer for further processing and viewing.

DQE–Detective Quantum Efficiency. Describes how clearly different structures appear in a digital image. Also refers to the efficiency that a detector converts x-ray radiation to an image.

EXPOSURE INDEX–The exposure index (EI) is a value representing the amount of radiation dose received by the image receptor. Equipment manufacturers provide a recommended EI range for optimal image quality.

FALLING LOAD–The mA waveform produced by a special type of x-ray generator. A falling load generator will initially produce the maximum mA allowable for the x-ray tube at the beginning of the exposure and then will drastically reduce the mA after a preprogrammed interval. The resulting radiation waveform will have a flat portion followed by a negative slope.

FORCED COMMUTATION (or forced extinction)–A method of quickly turning "off" an SCR contactor by actively removing the source voltage. The SCR is usually forced "off" by a second SCR.

GRAY–The international measurement of absorbed dose. 1 Gy = 1 joule of radiation energy absorbed per kilogram of tissue. 0.01 Gy = 1 RAD.

GRID–A device used in radiography that reduces scatter radiation, thus improving image quality. The grid is placed directly in front of the image receptor.

HEEL EFFECT–A phenomenon that occurs in all x-ray tubes where there is a variation in the exposure rate that coincides with the angle of emission from the focus of the tube. It is caused by the amount of target angle and the anode thickness. The radiation that travels toward the anode end of the x-ray field must pass through a small portion of the anode and is, consequently, attenuated. This results a slight decrease in radiation intensity and is clearly visible on the image.

HVL–Half Value Layer. A measurement unit that represents the quality of the x-ray beam. It is the amount of AL-1100 required to reduce the R output of the x-ray tube by 1/2. Federal guidelines for minimum requirements for HVL are provided so that patients will not receive excessive soft radiation (see Appendix A).

HIGH VOLTAGE DIVIDER–A test instrument used to visualize and measure the actual kVp waveform. This divider is essentially a metal tank which contains an internal resistor divider network surrounded by insulating oil. It is connected in series with the x-ray tube and used in conjunction with an oscilloscope.

H.U.–Heat Units. A measure of the power (heat) capacity of an x-ray tube. The amount of heat an x-ray tube can safely withstand is a function of the target size and tube housing type. One heat unit is equal to the product of kVp x mA x TIME for single phase generators. Because of the improved efficiency of a three-phase generator, the heat applied to the x-ray tube is increased by a factor of 1.35, for 6-pulse, and 1.41 for a 12-pulse system.

ILLUMINATOR–Also called a view box. A device used by radiologists for viewing radiographs.

INTENSIFYING SCREEN–The material that lines the inside of film and CR cassettes. Intensifying screens convert x-ray radiation to light radiation which then exposes the imaging media.

IMAGE RECEPTOR–A device that transforms x-ray radiation that has passed through the patient into a visible image. In radiography, the image receptor is the CR cassette and DR panel.

INHERENT FILTRATION–The amount of filtration that exists in an x-ray tube alone. The tube naturally has filtration caused by the combination of the glass insert, insulating oil, and tube housing port. The amount of inherent filtration should be an equivalent of .5mm of aluminum.

K-ABSORPTION EDGE–The threshold or limit, specific to the type of filter material used, above which radiation will be absorbed.

MAMMOGRAPHY–A specialized field of radiography developed for the screening and diagnosis of breast cancer.

MQSA–Mammography Quality Standards Act, established in 1994.

OID–Object to image distance. The distance from the object being x-rayed (i.e., phantom or patient) to the image media.

PHANTOM–A test device that simulates patient tissue and is used by field service engineers and radiation physicists for image evaluation. Phantoms are made of a variety of materials including acrylic, copper, aluminum, special fluids, and lead.

RAD (Radiation Absorbed Dose)–A unit of measurement indicating the amount of radiation absorbed by the patient. It is a measurement of the total entrance dose delivered in tissue. One RAD represents the absorption of 100 ergs of energy per gram of tissue.

REM (Radiation Equivalent for Man)–A measurement of radiation absorbed dose that is multiplied by a quality factor dependent on the type of radiation being used. For diagnostic x-ray radiation, 1 RAD = 1 REM.

RESOLUTION–A measurement of an imaging system's ability to produce sharpness. Also termed image sharpness or image definition.

ROENTGEN (R)–The unit of measurement of radiation (free in air). One R is defined as the amount of radiation required to produce one electrostatic unit (ESU) of charge in 1 cc of air under standard conditions of pressure, temperature, and humidity.

ROTOR–The rotating anode of an x-ray tube. The rotor is the moving part of induction motor.

SAFELIGHT–The light used in a darkroom that contains a low wattage light bulb and a special filter that will not expose x-ray film. The correct filter must be matched to the film being used.

SCATTER RADIATION–A characteristic of radiation caused by the interaction with matter. Scatter radiation adversely affects image quality by reducing image contrast.

SCINTILLATOR–The material used to convert x-ray energy to light energy in image receptors. Cesium Iodide (CsI) and Gadolinium Oxysulfide (Gadox) are two common scintillators used in CR and DR.

SCOUT FILM–A test film taken prior to a special procedures examination to ensure proper positioning technique.

SELF-COMMUTATION–A method of turning "off" an SCR by allowing the SCR to turn "off" with the naturally occurring zero crossover points of the AC line.

SENSITOMETER–A device used for processor quality control. It exposes film to produce a calibrated step wedge of increasing densities. Measurements are made with the resulting "strip" for film base fog, speed, and contrast indexes.

SHARPNESS–The abruptness of change between two adjacent densities (i.e., abruptness of the boundary) on an image. A fast change between two different densities that are adjacent to each other will produce a sharper image.

SID–Source to image distance. The distance from the focal spot of the x-ray tube to the image plane.

SIEVERT–The international unit for absorbed dose normalized for the type of radiation used. 1 Sv = 100 REM.

SPACE CHARGE–The cloud of electrons that forms around the cathode when the filament is heated.

SSD–Source to skin distance. The distance from the x-ray tube to the patient's skin.

STATOR–The stator windings of a rotating anode in the x-ray tube. The stator windings create the magnetic field which, through induction, causes the rotor to turn.

TOMOGRAPHY–A radiographic technique in which a slice of anatomy is imaged.

TRUNNION RINGS–A special tube mounting bracket that holds the x-ray tube in place and allows tube rotation.

VIBRATING REED TACHOMETER–A test instrument used by x-ray service engineers that measures the rotational speed of the rotating anode in an x-ray tube. This device senses the rotation of the anode by the frequency of vibrations felt through the tube housing.

ZONOGRAPHY–A technique used in tomography where a thick section, or zone, is imaged by using a very small tomographic angle.

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