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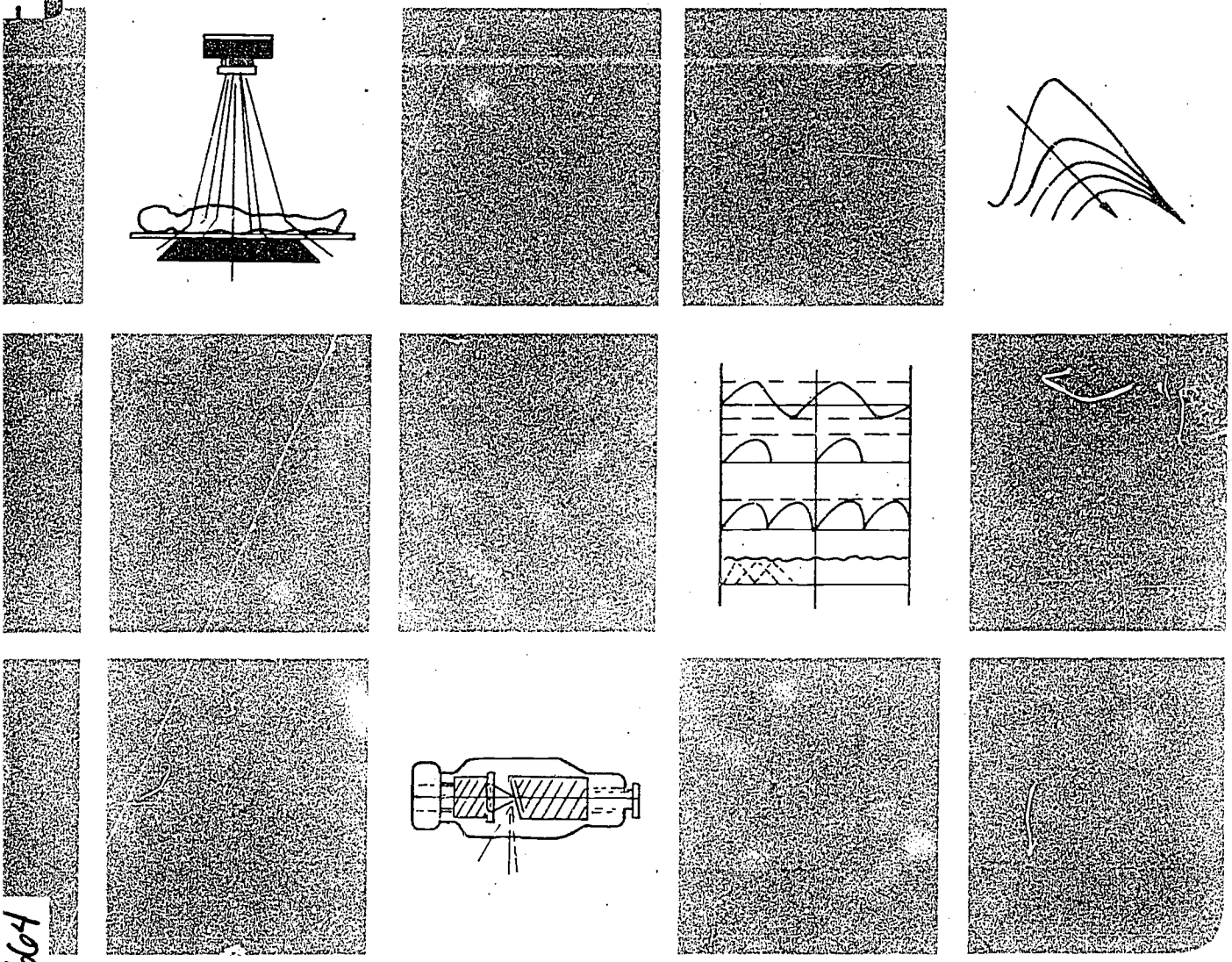
ABSTRACT

This series in diagnostic radiological physics has been designed to provide the physics background requisite for the proper conduct of medical diagnostic x-ray examinations. The basic goal of the series is to bridge physics theory and radiological practice, achieved by combining pertinent lecture material with laboratory exercises that illustrate the clinical applications under simulated clinical conditions. Nine chapters contain background physics information and laboratory exercises on the following topics: (1) x-ray production and machine output; (2) radiographic contrast; (3) subject contrast; (4) the control of scattered radiation; (5) intensifying screens; (6) radiographic film; (7) contrast and processing; (8) quality assurance of automatic film processing; (9) geometric factors in radiography; (10) x-ray quality assurance; and (11) reduction of unnecessary patient exposure. (CS)

The Correlated Lecture Laboratory Series in Diagnostic Radiological Physics



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FOREWORD

The Bureau of Radiological Health develops and carries out a national program to control unnecessary human exposure to potentially hazardous ionizing and nonionizing radiations and to ensure the safe, efficacious use of such radiations. The Bureau publishes the results of its work in scientific journals and in its own technical reports.

These reports provide a mechanism for disseminating results of Bureau and contractor projects. They are distributed to Federal, State, and local governments; industry; hospitals; the medical profession; educators; researchers; libraries; professional and trade organizations; the press; and others. The reports are sold by the Government Printing Office and/or the National Technical Information Service.

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WHO Collaborating Center for Standardization of Protection Against Nonionizing Radiations;

WHO Collaborating Center for Training and General Tasks in Radiation Medicine; and

WHO Collaborating Center for Nuclear Medicine.

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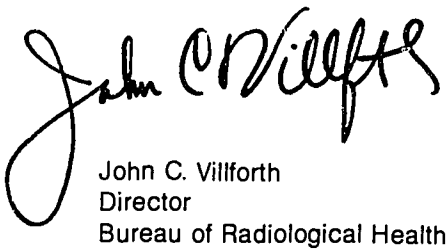

John C. Villforth
Director
Bureau of Radiological Health

PREFACE

The Correlated Lecture-Laboratory Series in Diagnostic Radiological Physics is an integrated educational system designed to provide the physics background requisite for the proper conduct of medical diagnostic x-ray examinations. The series is one part of a comprehensive teaching system for Radiology called the Radiological Learning Laboratory. The two other components of the Learning Laboratory provide instruction in radiographic interpretation and information regarding selection of patients for x-ray examinations.

The physics series consists of nine lectures, each accompanied by a laboratory exercise correlated to its key points. As such, this series has been designed as an aid to instructors in designing and presenting diagnostic radiological physics courses for radiology residents, student radiologic technologists, medical students, and others involved in the radiological process.

The basic goal of this series is to build a bridge between physics theory and radiological practice; this is achieved by combining pertinent lecture material with laboratory exercises that illustrate the clinical applications under simulated clinical conditions. Radiographic phantoms are used in most cases so the resultant films will be similar in appearance to those seen in the clinical department. The students themselves conduct the laboratory exercises and observe the final results on radiographs — the everyday commodity of radiology. By actually making the films, the students learn basic radiological techniques along with the underlying physics, and see how the resultant radiograph and its interpretation can be affected by changes in radiologic parameters. It also provides them with a hands-on experience to learn the operation of actual radiographic hardware.

The lectures encompass the minimum physics information felt to be needed for the knowledgeable operation of diagnostic radiographic equipment. Each lecture is presented in narrative fashion, rather than outline format, so that the approach and level of detail will be apparent. Some users will want to add to this material in their lectures and are encouraged to do so.

The document contains a number of generalizations which may be objectionable to some users, since exceptions to these generalizations are noted but not discussed in detail. Such exceptions were deliberately omitted because of their minimal importance in practical clinical applications, and because their adequate explanation would increase the size of this text and require a level of physics sophistication believed inappropriate for the intent and scope of this document. It is envisioned that these particular topics would be presented in subsequent more advanced physics courses.

The lectures and laboratory exercises in this document are not intended to be complete in themselves, but simply to provide a basic foundation for the student to build upon. The student is encouraged to experimentally pursue any question that may arise in his or her everyday work, or as a direct result of these exercises. The teaching x-ray unit that can be used in conjunction with these exercises is specially designed for this type of investigation: it can be installed in any laboratory or classroom, it does not interfere with the clinical service of the department, it cannot be readily damaged, and it presents no radiation hazard to the operator or others present. However, with appropriate modification of techique factors, the exercises can also be performed on a full-size general purpose radiographic unit.

The course is designed to be presented very early in the radiological career of the student, beginning within the first three months. Many of the concepts discussed will be encountered and learned in practice; however, it is far more efficient and productive to learn them in a logical sequence such as presented in this course, illustrated with specific examples.

The technique factors for the radiographs taken during the laboratory exercises were deliberately chosen to approximate the factors used in real clinical situations. However, the specific factors used in any situation are highly dependent upon the film processing conditions, type of radiographic film, and the particular cassettes used. Therefore the instructor may have to modify the technique factors in the exercise to suit his or her particular conditions.

The two chapters on quality assurance (Chapters 6 and 8) contain considerable detail regarding specific tests. This level of detail may not be appropriate for all groups of students who may take the course, and these lectures should therefore be tailored to meet the needs of a particular audience. The specific laboratory exercises associated with these two chapters are designed to illustrate the variability of film processing and of machine output within one's own

department. A cookbook performance of all of the quality assurance tests is not suggested, although this could easily be added if the instructor feels that it would be appropriate and useful to a specific group of students.

It is hoped that this coordinated approach to diagnostic radiological physics training will provide students with a memorable and insightful experience which is relevant to their roles in the clinical radiology process.

William S. Properzio, Ph.D.
Director
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CONTENTS

INTRODUCTION

The diagnosis of an abnormality from radiological evidence is the end product of a series of events comprising the "radiological process." This process consists of three distinct parts: the selection of a patient for an appropriate radiological examination, the conduct of the examination, and the interpretation of the examination. The end product of this process is a radiographic diagnosis. The division of the radiological process into selection, conduct, and interpretation is quite natural because in practice each portion may be performed (or supervised) by a different physician. The last step, interpretation, can be further subdivided into the detection of details, the description of those details and how they may deviate from a normal pattern, and an evaluation of the conditions that might cause the deviant details.

The quality of a radiograph is equated with the visibility of pertinent details, since they constitute the raw material of the interpretation and hence the diagnosis. Their visibility depends partly upon the subjective opinions of the interpreter, a topic outside the realm of this syllabus, but mainly upon the many physical factors chosen to conduct the examination. Therefore this lecture-laboratory series is designed to investigate the effects of these physical parameters on the quality of the resultant radiograph.

Radiographic quality, however, is not the only consideration in performing an examination. Ideally, the radiation dose to the patient should be minimized while the diagnostic information is maximized. Unfortunately, the factors that yield the best radiographic quality may also yield a high patient dose, so a compromise must often be made between needed quality and unavoidable patient dose. The laboratory exercises in this series will investigate the various factors listed in Figure 0-1 and the devices and techniques routinely used in clinical radiology. The resultant films will be compared not only on the basis of film quality but also on the basis of relative patient exposure.

PRODUCTION OF A RADIOGRAPHIC IMAGE

In order to produce a radiograph (or radiographs) for interpretation, a large number of decisions must be made. For example:

1. Can a radiographic procedure either completely or partially supply the diagnostic information required?
2. Is a dynamic procedure (e.g., fluoroscopy) required, or will individual radiographs suffice?
3. Is a contrast medium required to obtain the desired information?
4. What radiographic views are required?
5. What source-to-image receptor distance should be used?
6. What type of machine should be used (fluoroscopic, radiographic, single or three phase, high mA)?
7. What is the predominant composition of the subject (soft tissue, air, bone, contrast medium)?
8. What is the thickness of the subject?
9. Should a grid be used? If so, what grid?
10. Which intensifying screens should be used?
11. What type and speed of radiographic film should be used?
12. What kVp should be used?
13. What mA should be used?
14. What exposure time should be used?
15. What other devices should be used (e.g., patient immobilizing devices)?

Although the physician is ultimately responsible for the conduct of the examination, the radiologic technologist makes most of the decisions, either directly or by consulting a technique chart. The physician usually exerts his control by formal training of the technologist, by expressing his personal preferences of film quality, or by the formulation of the technique chart. Therefore, it is essential that he know how various physical parameters affect film quality and also how they affect the radiation exposure of the patient.

FACTORS AFFECTING RADIOGRAPHIC QUALITY

The quality of a radiograph, determined by the relative visibility of details depicted, is affected by many factors under the control of the operator. Detail visibility (Fig. 0-1), which is a measure of the resolving power or resolution of the imaging system, depends upon two completely independent physical factors — radiographic contrast and sharpness.

Radiographic contrast is the difference in optical density (darkness) between the image of an object and its surroundings. If this density difference is zero (contrast of zero), obviously the object would not be visible. *Sharpness* (definition) on the other hand, pertains to the boundary between the image of an object and the surrounding area. If this boundary is diffuse, a small object may be difficult or impossible to visualize, even with good radiographic contrast.

Radiographic contrast, that is, contrast visible on the developed film, is itself the product of two sources — the contrast due to the characteristics of the film and the developing process (film contrast), and the contrast due to the difference in radiopacity of the internal structure of the subject (subject contrast). Likewise, sharpness results from two sources — the geometric factors involved in the imaging system, and radiographic mottle produced by the film-screen imaging system. Each of these factors will be discussed in the various chapters of this document.

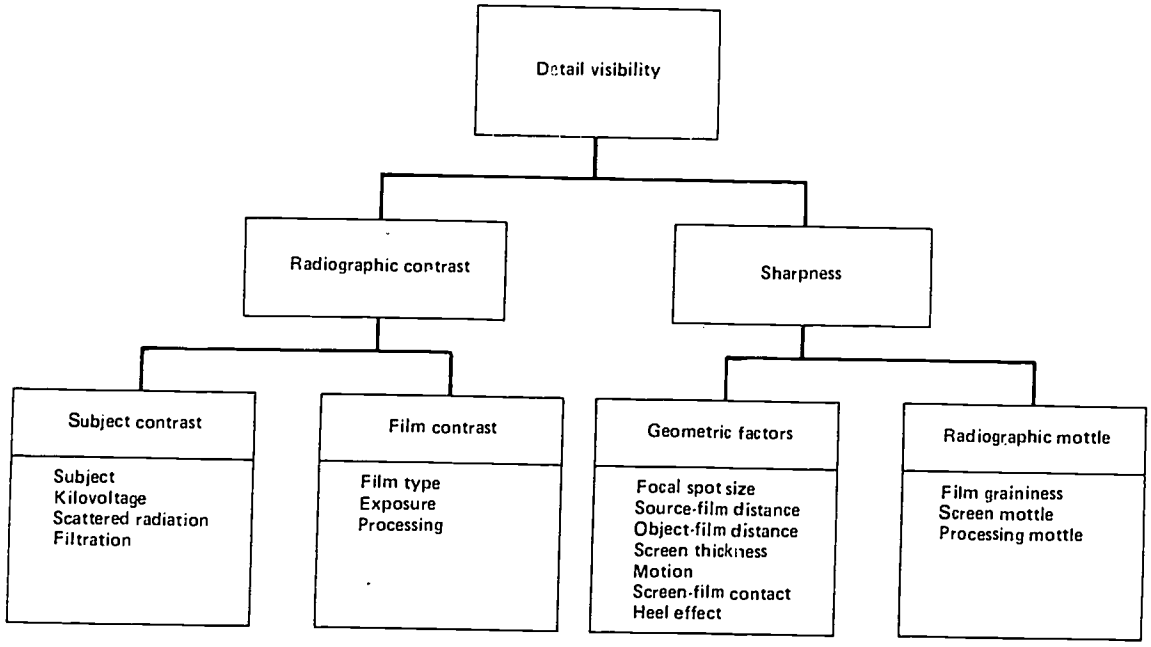


Figure 0-1. Factors that affect detail visibility, i.e., film quality.
(Adapted from talk given by George M. Corney, Eastman Kodak Company)

EQUIPMENT FOR THE LABORATORY EXERCISES

The Teaching X-ray Unit

The laboratory exercises in this document were designed for use with a commercially available cabinet x-ray unit, radiographic phantoms, grids, cassettes, and film processing equipment and chemistry. The specific equipment is mentioned only so that special technique factors can be utilized. This should not be construed as either an actual or implied endorsement of such equipment.

The specific x-ray unit used for these exercises is a Faxitron 8070-320, a small self-contained machine that can produce radiographs comparable to those from a full-sized machine. Specific features are:

1. The unit is shielded and meets the NBS recommendations for exempt installation. It can therefore be used safely in a clasroom or laboratory.
2. Both doors have interlocks to prevent exposure if either door is not completely closed.
3. The tube voltage is continuously adjustable from 10 to 130 kVp.
4. The tube current is continuously adjustable from 0 to 3 mA.
5. The kVp and mA controls are not truly independent; both will have to be adjusted whenever either value is changed.
6. The exposure timer can be set for up to 60 minutes.
7. Radiographs taken on this unit are identical to those taken on full-sized equipment. However, in making an exposure, the low mA must be compensated for by an increase in time.

8. In order to get properly exposed films, it is necessary to adjust the kVp and mA before the film is placed in the cabinet and the time is set.
9. Because of the low mA, these machines can be operated continuously without overheating the tube.
10. This unit is equipped with a beryllium window, which does not attenuate the beam significantly. Therefore the total filtration in the beam can be considered to be equal to the added filtration.
11. There are several slots provided at the top of the exposure cabinet for diaphragms and filters. In general, the diaphragm should be placed below any filters being used.
12. For these exercises the shelves are numbered from 1 to 6 starting at the top of the upper cabinet (1 to 3 in the upper cabinet, 4 to 6 in the lower cabinet).

Radiation-Measuring Instrumentation

There are many good dosimetry systems commercially available that can be used for the laboratory exercises. One limitation is that the connecting cable between the electrometer and the probe must be able to pass through the Z-access port in the back of the teaching x-ray unit. In addition, the dosimetry system should have the following features:

1. The meter should be capable of providing radiation measurements of both exposure rate and total exposure (i.e., it should have both a rate mode and an integrate mode).
2. The chamber should be sensitive to diagnostic energy x-ray beams.
3. The probe should be small enough to be centered in the 14″ × 17″ exposure cabinet.

The easiest systems to use are the auto-ranging digital units. Many students who are not accustomed to meter reading find multiple-scale meter units so distracting that their use interferes with the concepts to be learned. Low energy dosimeters can be used (with modification of the exercises) but their relative inaccuracy and lack of direct readout make data-taking very tedious.

Film-Screen Combinations, Grids, Processing Chemicals

Although other combinations may be used, the technique factors in this series have been refined for standard calcium tungstate film-screen systems. Obviously, film processing facilities must be available. Our processing chemicals were Kodak RP developer and fixer. We employed Liebel-Flarsheim 85 line per inch focused grids where grids were called for in the exercises.

General Equipment List

In addition, the following list of general equipment is required for the laboratory exercises:

Assortment of lead diaphragms
Assortment of aluminum filters
Plastic shelf for exposure cabinet (can be cut to size, 15¼″ × 18⅛″)
Radiographic film
Cardboard casssettes
Cassettes with par, detail, high speed, and very high speed screens
Damaged cassette to illustrate poor film-screen contact
Radiographic knee, pelvis, and hand phantoms
Magnification phantom (to be made by the instructor)
Distortion phantom (to be made by the instructor)
Aluminum stepwedge
Paraffin blocks
Wood supports (2 pieces of wood, 2″ × 4″ × 15″)
Lead numbers
Sensitometer (desirable but not mandatory)
Densitometer (desirable but not mandatory)

1

X-RAY PRODUCTION AND MACHINE OUTPUT

A prerequisite to the proper use of radiography as a diagnostic tool of clinical medicine is an understanding of the basic nature of x radiation and the methods of producing x rays. This is not suggested merely for academic interest; an understanding of x radiation and its interaction with matter is essential to the proper choice of operating parameters to be used in any particular clinical situation. Likewise, an understanding of the process of x-ray production will illustrate the operating limitations of x-ray machines and may prevent unproductive x-ray exposure and expensive x-ray machine damage.

RADIATION AND RADIATION SOURCES

For the purposes of this discussion radiation can be defined as the propagation of energy from point to point through space or through matter, although the range of propagation will be limited by any interactions that occur in the matter. There are two distinct categories of radiation: particulate radiation, which involves the transmission of energy in the form of the kinetic energy of subatomic and atomic particles (e.g., electrons, protons, neutrons, alpha particles, heavy ions, etc.) and electromagnetic (E-M) radiation, which involves the transmission of energy without the presence of a particle with mass (e.g., radio waves, visible light, and x rays).

Our environment has always been subject to naturally occurring radiation, the most obvious being light from the sun and stars. However, the sun and stars, along with other extraterrestrial sources, also shower us with x rays, radio waves, and particulate radiation such as energetic protons, neutrons, and atomic nuclei. At the same time, terrestrial sources are contributing radiation through the radioactive decay of naturally occurring radioisotopes such as uranium, thorium, radium, potassium-40, and carbon-14.

Man, with his technological advances, has also contributed sources of radiation to the environment: nuclear weapons and their fallout of radioactive isotopes; nuclear reactors with their output of neutrons and radioactive wastes; sophisticated particle accelerators; and the expanding numbers of medical and industrial x-ray sources. The most prevalent of all man-made radiation is often overlooked, namely radiation in the form of television and radio waves, visible light, and infrared radiation.

General Characteristics of Radiation

To repeat, radiation is the propagation of energy from point to point. *Particulate radiation* consists of a moving particle of some mass which possesses the energy of motion, kinetic energy. The more energy it possesses, the faster it must be moving(1). If it is stopped by an object, the energy is transferred to the object and the propagation of energy from point to point has been satisfied. Once the particle has stopped, it is no longer "radiation," but merely a particle.

The concept of electromagnetic radiation(2) is more difficult to comprehend. *Electromagnetic radiation* involves the movement of energy only in discrete bundles called energy quanta, or *photons,* often thought of as particles of zero mass. The different types of E-M radiation are radio waves, microwaves, infrared (heat), visible light, ultraviolet light, x rays, and gamma rays. The only distinction between these types of eletromagnetic radiation is the amount of energy per photon. They all travel at the same speed, the so-called speed of light, and do not exist at any other speed. Although the speed of light has slightly different values in different media, it is constant in any given medium (the speed of light in a vacuum = 3×10^8 meters/second).

The physical properties of E-M radiation can be mathematically described if these radiations are thought of as massless particles in some instances and as continuous waves in other instances. The ***wave nature*** of E-M radiation is best used to describe interference and diffraction phenomena. Although most people are familiar with these phenomena in association with visible light, the diffraction of x rays also occurs. (X-ray diffraction spectroscopy is an important tool in the study of crystalline substances.) Wave nature is also a basic criterion in the design of radio and microwave antennas. Since all E-M radiation can be mathematically described in terms of these sinusoidal waves, each particular radiation has a wavelength (λ — Greek letter lambda) and a frequency (ν — Greek letter nu). The frequency is defined as the number of complete wave cycles that will pass any point in one second (Fig. 1-1). Each different type of E-M radiation has a specific range of wavelengths and frequencies as shown in Figure 1-2, the electromagnetic spectrum, although the boundaries of these ranges are not exact.

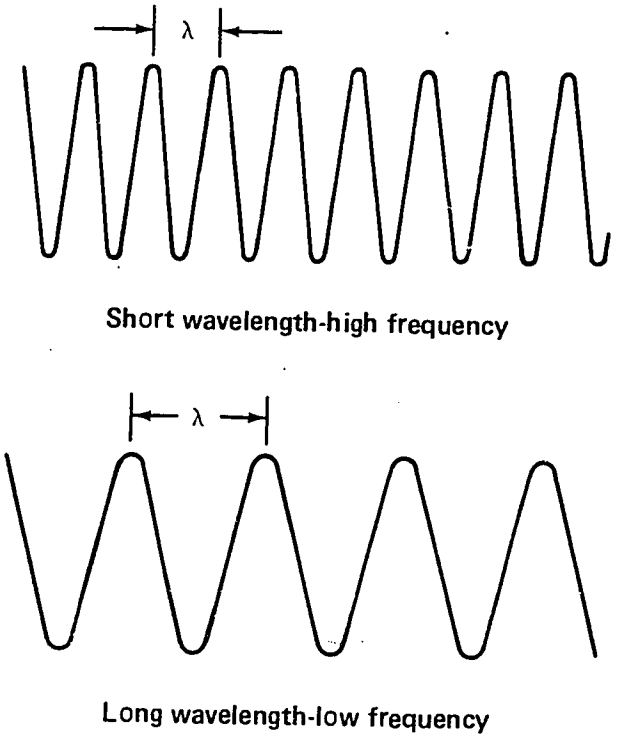


Figure 1-1. Wavelength-frequency relationship of electromagnetic radiation.

The particulate nature of E-M radiation is generally used to describe the interaction and energy-transfer processes between high frequency E-M radiations and matter. In general, any given photon must transfer all of its energy in an interaction process or none at all; there is no in-between. However, a second, lower energy photon may be released during the interaction (e.g., the Compton effect, see Chap. 2). This phenomenon is best illustrated by light and x-ray absorption interactions where there is a specific energy threshold requirement. If the energy of the incident photons is below that threshold, there will be no interaction even though there may be billions of such photons available, with a combined total energy far above the threshold. Only the full energy of one photon can be transferred to satisfy the threshold requirement, not a combination from multiple photons. The processes by which x rays interact with matter will be discussed in Chapter 2.

The wave and particulate natures of E-M radiation are theoretically and mathematically compatible. In fact, the wavelength, frequency, and discrete photon energy are mathematically interrelated(3); hence the specification of any one of the three defines the other two, and thus uniquely defines the radiation. Figure 1-2, the E-M spectrum, shows the interrelationship between photon energy, wavelength, and frequency. The low energy, long wavelength radiations are generally discussed in terms of wavelength while the high energy, short wavelength radiations are discussed in terms of photons and photon energy. This has come about largely because of efforts to explain the different phenomena primarily associated with these radiations. Consequently, one never hears about "radio rays" or "x waves" although theoretically these should be as acceptable as the more common terms.

Two other important characteristics of E-M radiation are that it travels in straight lines and that it has the ability to penetrate objects. The amount of material that the radiation can penetrate depends upon the composition of the material and the energy of the radiation. The medium energy radiations (such as visible light) do not penetrate very deeply, but the highest energy x rays and gamma rays (and also, paradoxically, the lowest energy radiations) can penetrate through large thicknesses. These two characteristics (penetration and straight-line motion) are particularly evident in the radiographic process. When x rays penetrate an object under consideration, some of them will interact with that object, but the remainder, after traveling in straight lines from the x-ray source, can then produce an image indicating the size, shape, and internal composition of that object.

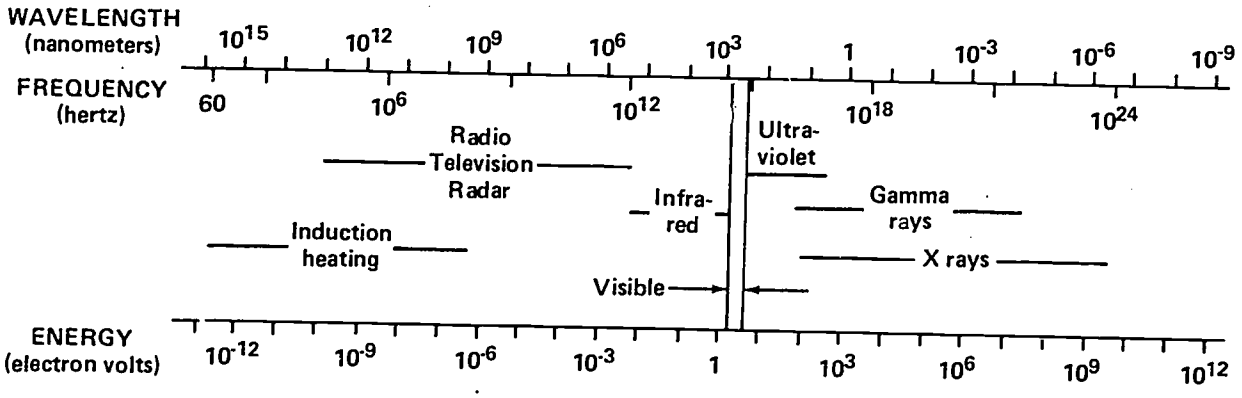


Figure 1-2. Chart of the electromagnetic spectrum.

Ionizing Radiation: X Rays and Gamma Rays

High energy E-M radiations will produce ions in passing through matter; thus they are termed *ionizing radiation*. The ionization process involves the transfer of energy from a photon to an electron that is bound to an atom. The energy must be large enough to overcome the binding force between the electron and its atom, resulting in a positively charged atom and a free negatively charged electron. The threshold for this ionization phenomenon depends on the binding energy of the target atom, but is in the neighborhood of 10 eV. (An electron volt, eV, is the amount of energy gained by one electron when accelerated through a potential difference of 1 volt. See also the section on Construction of an X-ray Tube, below.) Therefore, those radiations whose photon energies are greater than 10 ev, namely x rays, gamma rays, and some ultraviolet radiations, are classified as ionizing radiation. It is the ionizations and the chemical reactions produced by the resultant ions that cause the deleterious effects of ionizing radiation; the quantity of energy deposited by a fatal dose of ionizing radiation is insignificant in terms of the heat energy that a human can absorb safely.

Although x rays and gamma rays are classified as different types of electromagnetic radiation, the distinction between the two lies purely in the manner of formation: x rays are usually generated in machines in a controlled process, while gamma rays are emitted in the spontaneous nuclear decay of radioactive isotopes. However, once the individual photon has been created, there is no differentiating characteristic to indicate its origin as either a gamma ray or an x ray.

THE PRODUCTION OF X RAYS

X rays are produced as a by-product of the absorption of high-speed electrons in any substance. This process proceeds in a controlled manner within an x-ray tube. In a typical x-ray tube, electrons are accelerated to a high velocity and then allowed to collide with a "target." The interaction between the incident electrons and the target atoms results in the formation of x rays. The energies of the resultant x-ray photons range from very low values up to a maximum equal to the energy of the accelerated electron; it is not possible to produce a monoenergetic beam of x rays in this manner. Most electrons undergo multiple interactions and produce multiple photons of differing energies. The total energy of the incident electron will be converted to x-ray photons or heat in the target itself. The efficiency of x-ray production is very low in the energy range of interest for diagnostic radiology; only about 1% of the input energy is converted to x rays, the remainder resulting in heat. The problem of disposal of this superfluous heat imposes design and operating restrictions on diagnostic x-ray tubes.

Bremsstrahlung

There are two mechanisms by which x rays are produced, based on the type of interaction that occurs between the electrons and the target. The first process involves an electron traveling in close proximity to a nucleus of the target material. The attraction between the negatively charged electron and the positively charged nucleus causes the electron to be deflected from its original path with the loss of some of its energy. This kinetic energy lost by the electron is emitted as an x-ray photon (Fig. 1-3). The resultant radiation is known as general radiation, white radiation, or *Bremsstrahlung* (German, meaning "braking radiation"). Depending on the distance between the path of the incoming electron and the nucleus, the electron may give up any portion of its energy, up to and including its total energy. Thus, the energies of the emitted Bremsstrahlung photons will range from a very low value up to the total energy of the incident electron.

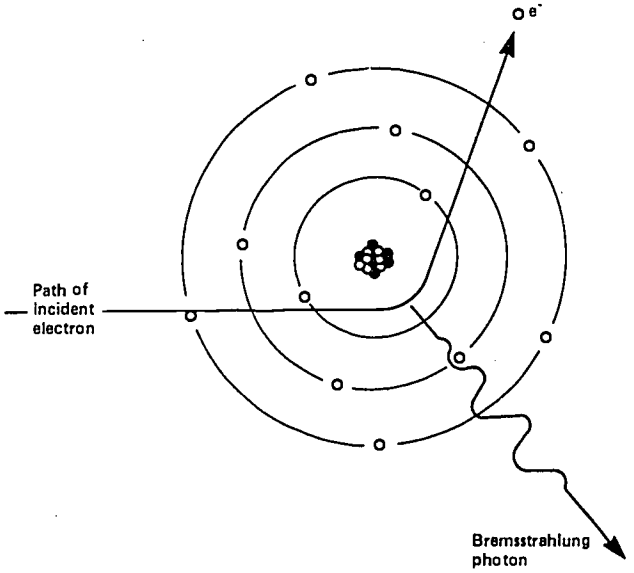


Figure 1-3. Generation of Bremsstrahlung.

Characteristic Radiation

The second x-ray production process involves a "collision" interaction between the incident electrons and an orbital electron bound to an atom in the target. This is illustrated in Figure 1-4. The incident electron transfers sufficient energy to the orbital electron so that it is ejected from its orbit, leaving a vacancy. This unstable condition is rectified by an electron moving from a higher shell into the vacancy. The transition of an electron to a lower shell results in a decrease in its potential energy, and the excess energy is emitted as an x-ray photon. This "filling"

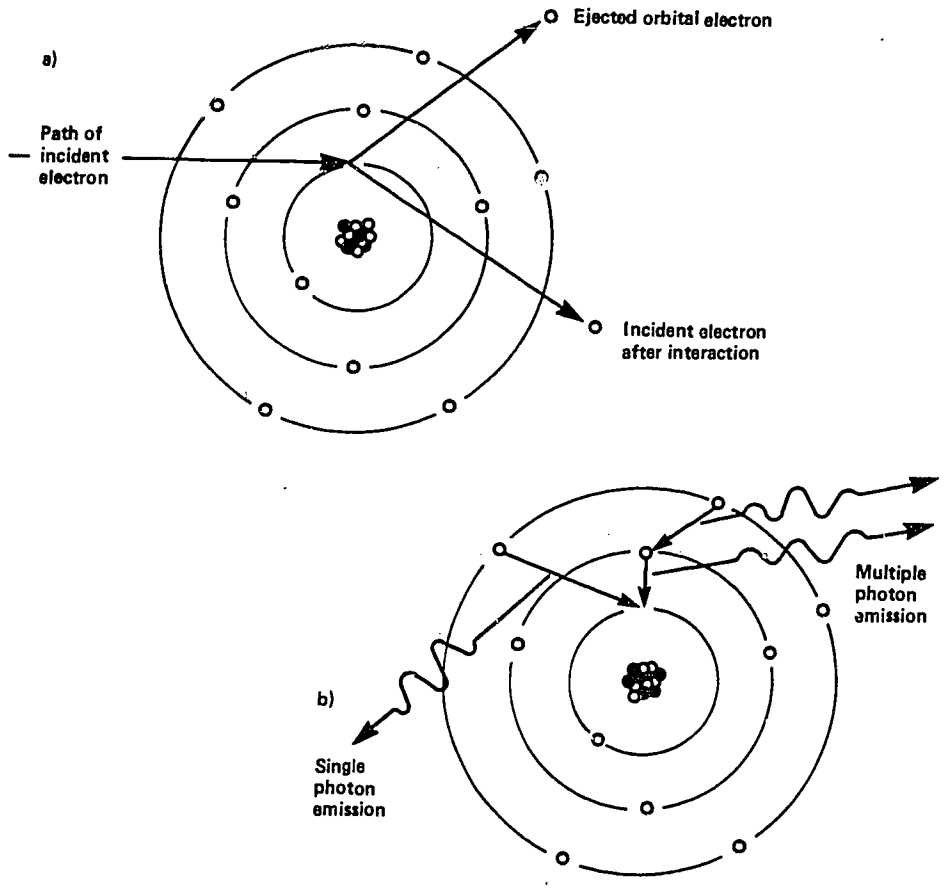


Figure 1-4. Generation of characteristic radiation:
a) Ejection of orbital electron
b) Emission of characteristic photons

process can take place in a single transition (one photon emitted) or multiple transitions (multiple lower energy photons emitted). Since the electron shell energy levels are unique to each element, the transition energies between different levels are also unique or characteristic; therefore the transition x rays are called *characteristic radiation.*

Following either of these two processes, the deflected incident electron goes on to engage in further interactions with target atoms until its total energy has been dissipated; that is, it is totally "stopped" by the target. It should be emphasized that the incident electron per se is not converted into a photon; rather it is the kinetic energy of the electron that is converted into photons and heat energy. After giving up all of its energy at the target, the electron simply continues on as part of the electrical circuit of the x-ray tube.

Construction of an X-ray Tube

A modern x-ray tube is actually a relatively simple device that is complicated by design criteria. As shown in Figure 1-5, it consists of an evacuated glass envelope containing a cathode and an anode. Free electrons are produced at the cathode and are accelerated to the anode by a high voltage applied between the cathode and anode. The high speed electrons bombard the anode (also referred to as the target) and produce Bremsstrahlung and characteristic x-ray photons. A portion of these x rays pass out of the tube and form the x-ray beam.

A slightly more detailed description of the x-ray tube will illustrate the controls and restrictions of an x-ray system. Free electrons are produced by electrically heating the filament, part of the cathode structure, to about 2000°C. The thermal energy imparted to the electrons is sufficient to overcome the atomic forces binding them to the atoms of the filament. This process is known as *thermionic emission*. The electrons freed from the filament are increased in energy by acceleration through the high voltage applied between the cathode and the anode. By definition, an electron starting from rest and accelerated through an electrical potential difference of 1 volt will gain an energy of 1 electron volt (eV). The

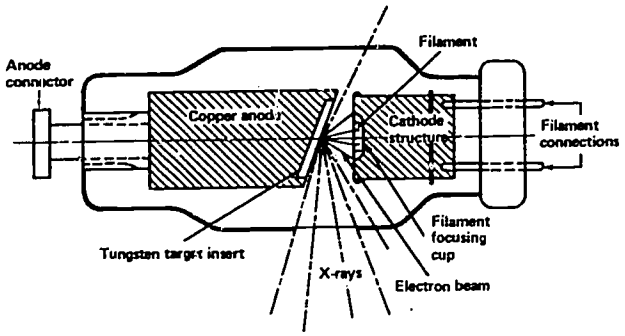


Figure 1-5. Stationary target x-ray tube.

voltages involved in x-ray production are in the thousand volt, or kilovolt (kV), range. An electron accelerated through 80.000 volts (80 kV) would gain a kinetic energy of 80 keV (kilo electron volts).

However, not all of the electrons will receive that energy. The high voltage supplied to the tube is an alternating current, which means that the voltage varies rapidly between zero and the maximum voltage supplied by the high voltage power supply(4). By convention, the voltage is described in terms of its peak kilovoltage (kVp). The electrons that reach the anode will have different energies (measured in keV) depending upon the value of the high voltage at the time when they passed across the tube. This fact, plus the fact that Bremsstrahlung photons vary in energy from zero to the maximum electron energy, means that there will be many low energy x-ray photons and very few with the maximum possible energy. (See the section on X-ray Spectra, Effect of High Voltage Supply, below.)

Basically, there are only three controls on an x-ray machine: the ***kilovoltage control***, which determines the maximum high voltage applied across the tube and as a result, the energy of the x-ray photons produced; the ***tube current control***, which determines the rate at which electrons flow across the tube and as a result, the rate at which x-ray photons are produced; and the ***timer***, which determines the total time during which x rays are produced. The tube current, measured in milliamperes (mA), is actually determined by the voltage and current of the filament circuit, which determines the temperature of the filament. Although the two circuits are separate, the filament circuit controls the electron flow (the current) in the x-ray circuit and therefore the rate of x-ray production. Therefore the mA control is calibrated and labeled in accordance with its effect on the current flowing in the x-ray circuit.

As stated above, the efficiency of x-ray production is very low in the diagnostic energy range. Of the total electron energy carried to the anode, about 99% (depending on the voltage) results in heat which, unless eliminated, will damage the anode. Therefore, the ***anode*** must have the following qualities: a high atomic number, a high melting point, and a high rate of heat dissipation. The first criterion is necessary because the efficiency of x-ray production is roughly proportional to the atomic number of the target atoms. In the choice of anode material, however, a compromise must be made, since the highest atomic number materials (such as lead) are easily melted and therefore cannot withstand the heat generated by x-ray production. The most suitable target material from all standpoints is tungsten. It has a reasonably high atomic number and a high melting point. But since copper has a higher heat conductivity and therefore can better dissipate the heat than tungsten, the anode structure is often made of copper with only a small piece of tungsten, called the "target," imbedded in it. Tubes of this design (Fig. 1-5) are known as ***stationary anode*** tubes.

That particular region of the target which is bombarded by electrons from the cathode and which produces the x rays is called the ***focal spot.*** By proper design of the cathode, the electrons can be focused onto the target in any size and shape focal spot that is desired(5). The focal spot should be as small as possible so that "good" resolution of small details in the object being x-rayed can be achieved (this will be dealt with in Chap. 6). Also, to reduce artifacts due to motion of the object, the exposure time should be as short as possible (also discussed in Chap. 6). Unfortunately, if both these conditions were met, it would result in such a high intensity of electrons falling on the focal spot and so much heat being generated that the tungsten would melt before the heat could be carried away. Therefore, compromises in focal spot size and tube operation must be made.

X-ray photons are emitted in almost equal numbers in all directions from the target, a fact that is exploited in decreasing the heat problem. If the target face is oriented at some angle (usually 20°) with respect to the cathode as shown in Figure 1-6, the focal spot appears to be

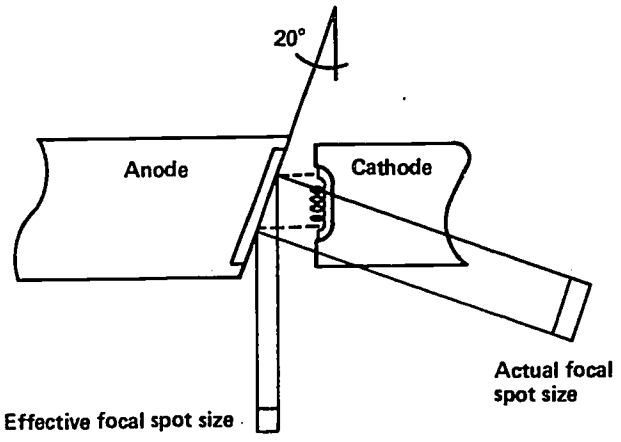


Figure 1-6. Focal spot size.

smaller than it actually is, that is, the effective focal area (which determines resolution characteristics of the x-ray beam) is smaller than the actual focal area (which determines the heat distribution and thus limits the rate of x-ray production). At 20 degrees, the actual area is about three times the effective area. Nevertheless, high intensity x-ray exposures often require that a larger focal spot be used to spread the electron bombardment over a larger area, or that longer exposure times be employed to decrease the rate of heat production.

The stationary anode tube design is commonly used in dental radiography and in therapeutic radiology, although therapeutic tubes generally have special anode cooling systems. (The tube in the teaching unit is also a stationary anode type.) However, almost all medical diagnostic tubes are now of the *rotating anode* type. The rotating anode principle greatly increases the actual focal area by making the anode a rotating tungsten disk, as shown in Figure 1-7. As heat is generated the disk is rotating, constantly bringing cooler regions of the anode into the electron beam. Thus, the actual focal area is a large ring, and as a result, the tube can be designed with a much smaller effective focal spot than a stationary anode tube. However, because the anode must be rotated at high speed so that the heat is distributed even in very short exposures, the rotating anode tube is inherently a complicated device and consequently is more expensive and less reliable than a stationary anode tube.

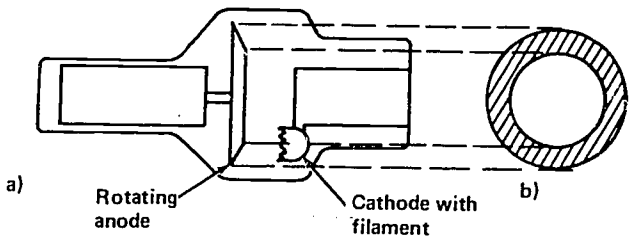


Figure 1-7. Rotating anode tube:
a) Side view
b) End view of anode (showing actual focal area).

All diagnostic x-ray tubes are supplied with *rating charts* which give the maximum allowable values of kilovoltage, milliamperage, and time that the tube can tolerate in one exposure. Exceeding these limits will probably result in localized damage to the focal spot region. Most tubes also have a cooling chart, which gives the time intervals necessary between exposures so that the total heat limit of the anode and the structure enclosing it will not be exceeded; this would cause more generalized damage.

In most schematic diagrams of an x-ray system, the x-ray beam is depicted as a small, well-defined field emanating from the tube target and incident on the patient. This is a rather misleading image. As stated above (in discussing the heat problem), x rays in the diagnostic energy range are emitted in roughly equal numbers in *all* directions. Only a small proportion of these x-ray photons can be effectively used in exposing a radiograph; the remainder must be eliminated. This is accomplished by enclosing the entire x-ray tube within a *housing* that is lined with lead shielding except for an x-ray "window." Since lead is very efficient in absorbing x-ray photons (as you will see in Chap. 2), only the *useful* beam passes out of the tube through the window, the remainder of the x-ray output, which is a large percentage of the total, having been eliminated. The elimination of these extraneous x rays is simply another factor contributing to the inefficiency of the x-ray production process. Besides the shielding function, the housing contains the electrical coils for rotating the anode, oil for transmitting heat from the tube to the housing (where it is transmitted to the surrounding air), and insulated connections between the high voltage cables and the cathode and anode.

The *window* is generally a glass section of the tube housing which is positioned close to the glass envelope of the tube itself. Therefore, the x-ray beam passes through two layers of glass but a minimum of oil. Although some x rays are absorbed in the glass, most of these are extremely low energy photons, which are not very productive in a radiological examination. In some special cases where these low energy photons are necessary, special x-ray tubes are made with only a beryllium window between the tube and the outside of the housing. Because of its low atomic number ($Z = 4$), fewer low energy photons are absorbed in the beryllium window as compared to a glass window. These special tubes are mainly used for radiobiological research. Because of the intense low energy component of the beam, the tube should be checked for the proper amount of added filtration with every use of the machine. (See the section on Effect of Filtration, below.)

Beyond the window, there are two other important parts of the x-ray head: the filter holder and a device for limiting the beam area. *Filters* (usually sheets of aluminum) are placed in the beam to alter the relative proportions of high and low energy photons in the beam. In general, the low energy photons contribute little to a radiologic image especially when examining thick parts, because of their poor penetration. Aluminum filtration absorbs many of these low energy photons before they can reach the patient, without appreciably affecting the higher energy photons. Proper filtration, therefore, results in decreased patient exposure.

The x-ray beam area is limited by using either *collimators,* devices with adjustable lead jaws to alter the size and shape of the field; or *cones,* metal tubes that yield a predetermined size and shape field. By keeping

the x-ray field as small as possible, not only is the patient exposure significantly reduced, the resulting radiographic image is also improved (to be discussed in Chap. 3).

X-RAY SPECTRA

The relative distribution of different photon energies in a photon beam has significant effects on the radiological examination. The contrast of the image, the thickness of patient that can be radiologically visualized, the exposure to the patient, and the amount of stray radiation in the room are all affected by the photon energy composition of the beam.

The photon energy distribution of an x-ray beam is described graphically by an energy spectrum. This is obtained by plotting the photon energy along the x-axis and the relative number of photons of that particular energy along the y-axis. A typical energy spectrum for a beam incident on a patient is shown in Figure 1-8. The maximum photon energy expressed in keV is equal in magnitude to the peak accelerating voltage (kVp), but there are very few photons of this energy. The number of photons increases with decreasing energy down to about 30 keV, where it is decreases again and essentially becomes zero at about 10-15 keV. This smooth curve is the spectrum due to Bremsstrahlung interactions. Imposed on top of this spectrum are some "spikes" due to characteristic radiation. The particular energy of these spikes depends on the material of the target. For a tungsten target, there are two spikes at about 58 keV and two at abcut 68 keV. These spikes are a minor portion of the overall spectrum and require a minimum tube voltage of 70 kVp for formation. The actual shape of the energy spectrum is strongly influenced by three factors: the filtration in the beam, the tube voltage, and the particular type of high voltage supply.

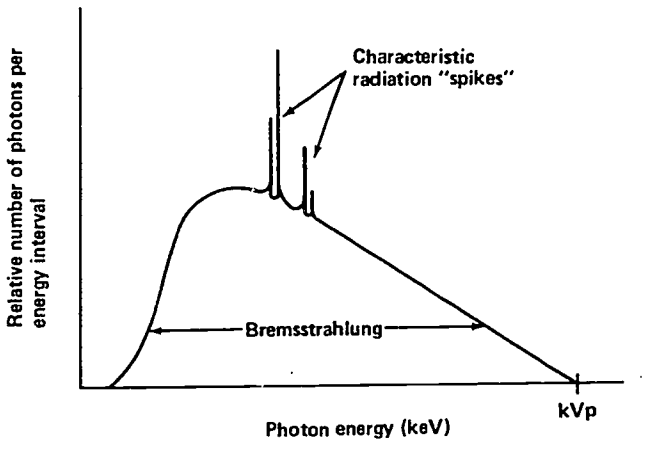


Figure 1-8. Generalized x-ray spectrum.

Effect of Filtration

An x-ray beam passing through any material will be reduced in intensity because of photon absorption within the material (to be discussed in Chap. 2). The photon loss is not equal across the energy spectrum since a low energy photon is more likely to be absorbed than a high energy one. (Therefore, high energy photons are said to be "more penetrating" than low energy ones.) If the material in question is a patient (composed of different amounts of air, soft tissue, and bone), the beam absorption will be nonuniform across the x-ray field. This nonuniform absorption consequently yields a nonuniform emergent beam containing information about the internal structure of the patient. Even though many photons are absorbed within the patient, obviously some must pass through to the imaging device or there will be no information transmitted. For this reason, the extremely low energy photons are useless in a radiological examination since they will be essentially completely absorbed within the patient across the entire field and will not yield any information about the internal structure. Therefore, it is desirable to eliminate the low energy photons from the beam while retaining the higher energy photons which will penetrate the patient and result in some radiographic information. This is accomplished by placing some suitable material in the beam to "filter" out the low energy photons. The total filtration in the beam actually consists of two portions, the inherent filtration and the added filtration. The inherent filtration includes all of the parts of the x-ray tube through which the beam passes, namely the glass tube envelope, the insulating oil, and the window. Added filtration is purposely placed in the beam to achieve the desired total filtration. Aluminum is generally used for this purpose in radiography, but copper, aluminum, and tin combinations are often used in x-ray therapy.

Figure 1-9 illustrates the effect of filtration on x-ray energy spectra; the spectra are measured at various distances from the focal spot after the beam has passed through different amounts of aluminum filtration. Spectrum A is the theoretical energy distribution that would be observed *at* the focal spot of the x-ray tube, if it could be measured. Unlike the spectrum in Figure 1-8, this one includes photons of all energies down to a theoretical limit of zero. In the Bremsstrahlung production process, most electrons undergo multiple interactions, distributing their energy to many low energy photons rather than giving up all their energy to a single photon. Therefore, the number of photons increases with decreasing photon energy. This is intuitively evident if you think of the nucleus of an atom as being in the center of a circular target that extends out as far as the effective interactive force between the nucleus and a moving electron. An electron passing through any part of that area can create a Bremsstrahlung photon, but only a direct hit will

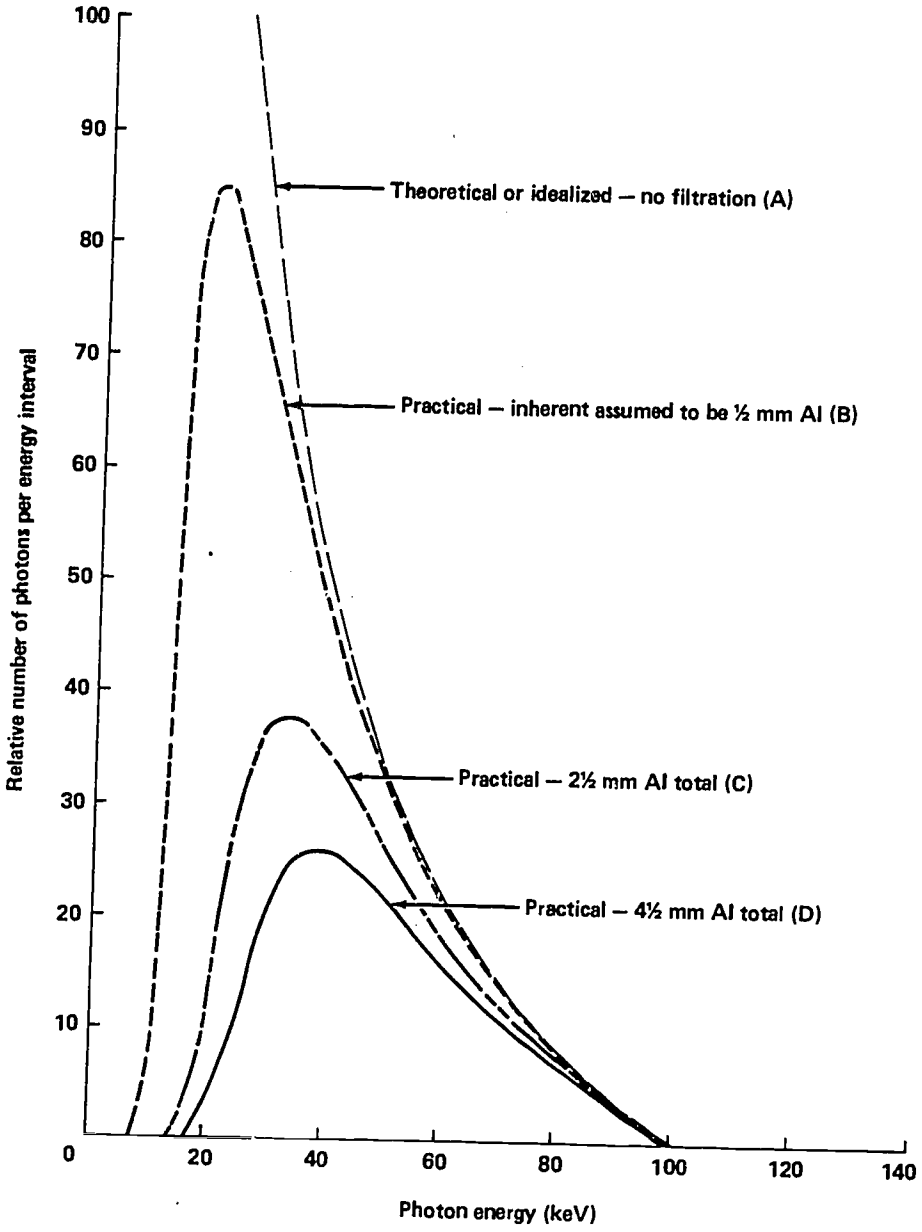


Figure 1-9. Effect of filtration on Bremsstrahlung spectra — 100 kVcp.

produce a maximum energy photon. Therefore, the probability of low energy photons being produced is far greater than the probability of high energy photons being produced.

Spectrum B shows the energy distribution after the beam has passed through the inherent filtration. The number of low energy photons has been reduced tremendously while the number of high energy photons has been relatively unaffected.

Spectrum C and spectrum D are measured after the beam has passed through different amounts of added filtration. This merely extends the process started by the inherent filtration, that is, the composition of the beam is changed by decreasing the percentage of low energy photons (this increases the average photon energy of the beam). In the process, of course, the number of photons of *all* energies is decreased, but the percentage of low energy photons lost is far greater.

There is no definite amount of filtration that is "best" for a radiographic procedure. As more filtration is added, a point will be reached that will result in visible changes in the radiograph. This will be at a lower filtration level for the radiograph of a hand, which is easily penetrated, than for the radiograph of an abdomen. Therefore, the proper amount of filtration for a multipurpose machine is difficult to determine. The National Council on Radiation Protection and Measurements (NCRP) gives the following recommendations:

Operating Tube Voltage	Minimum Total Filtration (Inherent plus added)
Below 50 kVp	0.5 mm aluminum
50-70 kVp	1.5 mm aluminum
Above 70 kVp	2.5 mm aluminum

Note that these are minimum amounts of total filtration required to meet the currently accepted standards of protection; many machines are used routinely with greater amounts of filtration. In many cases, the visible changes caused by extra filtration do not reduce the total information content in the radiograph and the diagnosis is not affected, while the patient exposure is significantly reduced. The radiologist, however, may have to learn to "interpret" films that are different in appearance from what he is accustomed to viewing.

Beryllium window x-ray tubes have very little inherent filtration and produce an x-ray spectrum similar to spectrum A. Their use without added filtration is not warranted in diagnostic radiology because of the intense radiation fields and the tremendous skin dose delivered. With appropriate safeguards, they are useful for training purposes since the total filtration can be decreased to essentially zero.

Two terms commonly encountered in the discussion of x-ray beams are quantity and quality. *Quantity* refers to the total number of x-ray photons in the beam. The quantity is always decreased as filtration is added. *Quality* refers to the average energy of the beam. As filtration is added and low energy photons are selectively removed, the average energy of the beam increases (higher quality). However, as the quality increases, i.e., the percentage of photons in the beam capable of penetrating a given thickness of material increases, the quantity of photons decreases.

Effect of Tube Kilovoltage

Increasing the accelerating potential that is applied to the x-ray tube appreciably changes the energy spectrum (Fig. 1-10). The number of photons of all energies is

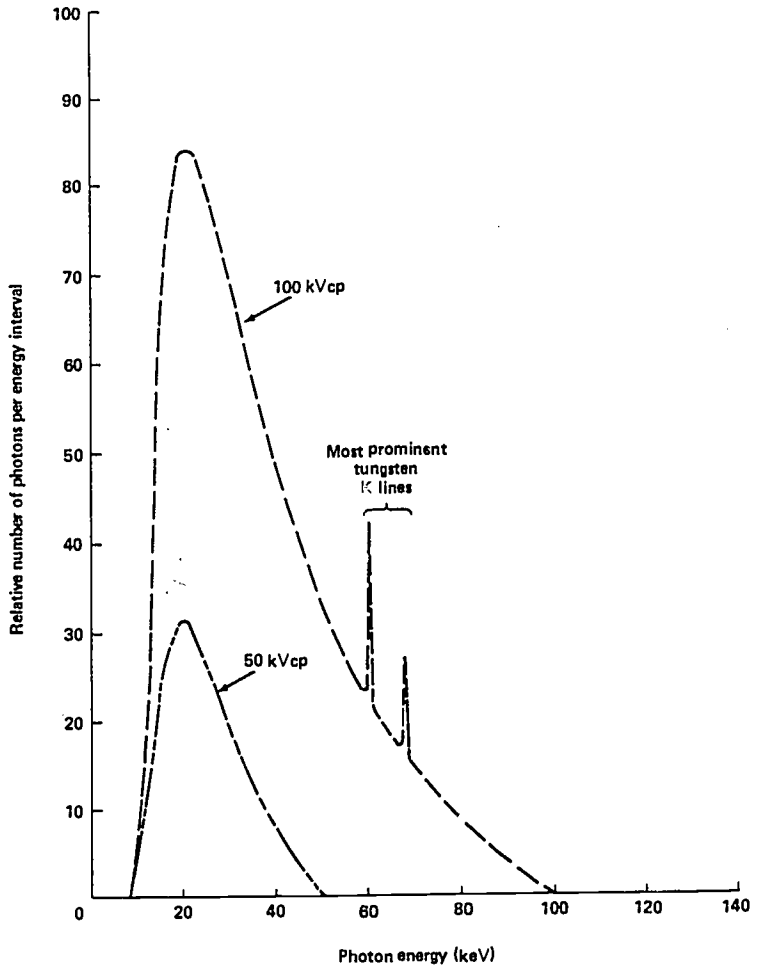


Figure 1-10. Effect of kV change on x-ray spectra.

increased, but more importantly, many higher energy photons are added. As was the case with increasing filtration, the average photon energy is increased. However, adding high energy photons to the beam will have a greater effect on the resultant radiographic image than removing low energy ones.

Effect of High Voltage Supply

In all x-ray circuits the voltage is increased by a transformer from the line voltage of 110 or 220 volts to the desired kVp. The electrical waveform looks the same as the waveform of the supply line, but greatly increased in amplitude.

Electrical power is produced as alternating current (ac). If one were to measure the voltage of an ac line, it would vary smoothly from zero to a maximum, back to zero, to a negative minimum, and back to zero again (Fig. 1-11a). Electrical current produced in the U.S. has 60 such cycles per second. In effect, current flows forward and backward 60 times each second. Although much electrical apparatus is not sensitive to the direction of electron flow, an x-ray tube cannot tolerate electron flow from the anode to the cathode. This problem is solved by the appropriate design of the x-ray circuit and involves some method of ***rectification,*** that is, some process by which the negative ac voltage cycles are eliminated.

In the simplest x-ray circuit, the x-ray tube is connected across the secondary winding of the transformer. In this case the x-ray tube itself serves as the rectifier, since current can only flow through the circuit when the target is positive with respect to the filament (i.e., during the positive potential portion of the ac cycle). During the negative potential portion of the ac cycle, there are no free electrons available at the target (which is now negatively charged) to be attracted to the filament (which is now positively charged). In this ***self-rectified*** x-ray tube, however, as electrons hit the target, they heat it to extreme temperatures. At such high temperature, electrons can boil off the target and during the negative potential portion of the ac cycle, the electrons may be accelerated back toward the delicate filament and destroy it. This is the reason for the development of half-wave and full-wave rectified circuits. In a ***half-wave rectified*** circuit the negative potential portion of the ac cycle is eliminated with a separate rectifier, the voltage remaining at zero during that portion of the cycle. Hence electrons are not accelerated toward the filament and the x-ray tube has a greater life expectancy.

In a self-rectified or half-wave rectified circuit, the electron flow is blocked during the negative part of the cycle so only half of the total cycle is used (Fig. 1-11b). In a ***full-wave*** rectified circuit the negative portion of the cycle is inverted (Fig. 1-11c) and there are twice as many useful pulses per second as in the previous case. Thus,

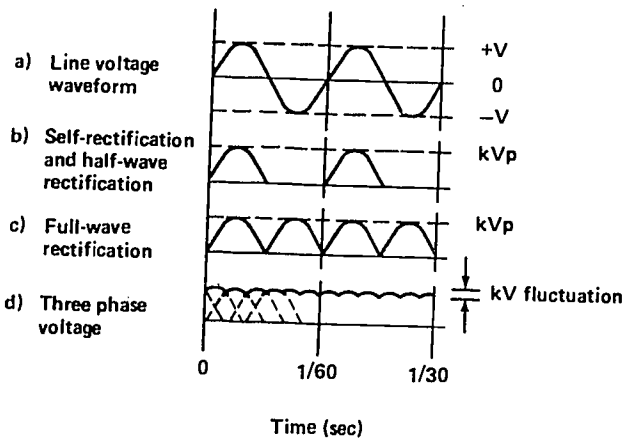


Figure 1-11. Electrical waveforms.

full advantage is taken of the whole electrical cycle.

In both the half-wave and full-wave rectified circuits, the voltage applied to the tube varies between zero and the peak kV, and can be referred to as a pulsating potential. Thus at any instant in time the x-ray energy spectrum is different, and the spectrum summed over a complete exposure has more low energy photons than it would if the voltage were constant. Most x-ray systems use a full-wave rectification circuit because of its relative simplicity and efficiency.

A further refinement is the use of a ***three-phase*** x-ray generator (Fig. 1-11d). The voltage supplied to the tube varies from the peak to a minimum of about 20% less than the maximum, although with various circuit modifications this variation can be decreased to about 5%. In this case, the voltage may be referred to as constant potential (cp). Since the voltage applied across the x-ray tube is never at a low value, the energy spectrum for a three-phase generator is shifted to the right of the spectrum for a single-phase (full-wave or half-wave rectified) generator (Fig. 1-12). For the same generator settings, more x rays will be produced having a higher average energy. Consequently, the radiographic technique factors (i.e., kVp, mA, and exposure time) appropriate for a particular procedure will be different if the tube voltage of the x-ray unit is constant potential.

Effect of Milliamperage

Variation of the milliamperage has ***no effect*** on the energy spectrum. Theoretically, the mA only affects the rate of x-ray production, not the energy of the photons(6). The combination of mA and exposure time (in seconds) determines the total number of x rays produced at any given kVp (mA multiplied by seconds of exposure equals the exposure factor called mAs). As a result, the mA can be changed, and as long as the time is changed accordingly (to keep the mAs constant) there will be no difference in the radiographic image.

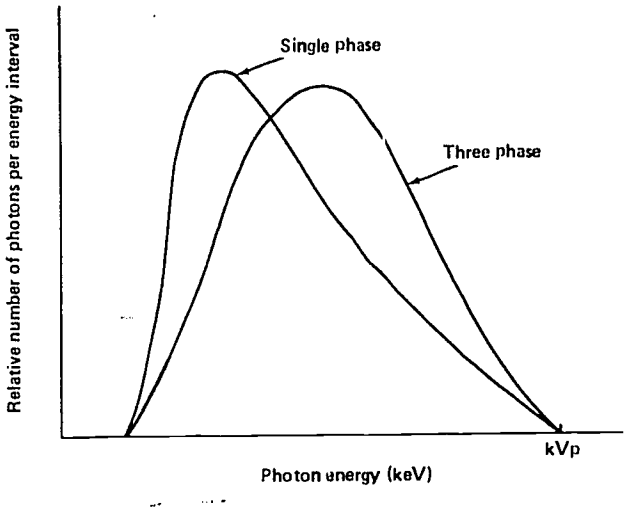


Figure 1-12. Three phase vs. single phase x-ray spectra.

To summarize, filtration, kilovoltage, and type of generator all affect the energy spectrum of the x-ray beam. However, the latter two factors have the greatest effect on the high energy photons which play a larger role in the formation of the radiographic image. Filtration affects the low energy photon distribution and therefore does not have as appreciable an effect on the image but does have a significant effect on the patient skin dose. However, if the average photon energy of the beam is increased by any method, thus making the beam more "penetrating," the total radiation dose to the patient will be reduced.

MEASUREMENT OF X-RAY BEAMS

Half Value Layer

The "penetrating ability" or quality of an x-ray beam is described explicitly by its spectral distribution. However, the spectrum concept is difficult to work with. For instance, it would be difficult to estimate the average energy of a beam after passing through some object. A more useful concept to describe and measure x-ray beam quality is the half value layer (HVL). The half value layer is defined as that thickness of a standard material which is required to reduce the number of x-ray photons transmitted to one-half their original number. The material ordinarily used for HVL determinations in diagnostic radiology is aluminum. A beam of low energy photons will be greatly reduced by a small amount of filtration (see the previous discussion on Effect of Filtration) and hence will have a low HVL; the higher the average photon energy of the beam, the higher the HVL, since the high energy photons are much less affected by the aluminum filtration. (Most diagnostic x-ray machines are operated above 70 kVp and have HVL's of 2.5-3 mm aluminum.) From the previous discussion about filtration, we also realize that the HVL is not a constant quantity but increases with increasing filtration, since the average beam energy increases. Therefore, the second HVL, the amount of material required to reduce the intensity of the beam from one-half to one-fourth (one-half of one-half) of its original value, will necessarily be greater than the first HVL. Only a monoenergetic beam of photons would have equal successive HVL's and such an x-ray beam is not practical for diagnostic radiology. (Cobalt-60 therapy machines do emit essentially monoenergetic gamma ray beams of equal successive HVL's.) Additional filtration selectively removes the lower energy photons and results in a better approximation of a monoenergetic beam. Therefore, the difference between successive HVL's gets smaller and smaller, although there will always be some increase between successive HVL thicknesses.

Exposure and Exposure Rate

The direct measurement of the energy carried by an x-ray beam is difficult to accomplish and could not be used for routine monitoring of x-ray output. Therefore, an indirect measurement of the effect of the x-ray beam on another system must be used. Various indirect methods employed have been biological methods (erythema production, destruction of bacteria); chemical methods (Fricke dosimeter which utilizes the oxidation of Fe^{+2} to Fe^{+3}); physicochemical methods (film dosimeters); and physical methods (thermoluminescent dosimetry, scintillation crystals, ionization of gases). The presently accepted standard is the measurement of the ionization produced in air by the x-ray beam, which was chosen because of its reproducibility and simplicity. It is based on the fact that the amount of ionization in a small volume of air surrounding a point of interest is proportional to the energy carried by the beam at that point. The amount of ionization that occurs in a small volume of air is defined as ***exposure,*** and the special unit of exposure is called the ***roentgen*** (R), defined as that amount of exposure necessary to produce 1 esu of ions of one charge per 0.001293 gram of air (the mass of 1 milliliter of air at standard temperature and pressure). An equally important and widely used unit is the milliroentgen (mR) which is one-thousandth of a roentgen. One roentgen is also defined as the exposure necessary to produce 2.58×10^{-4} coulomb of ions of one sign per kilogram of air. In the International System of Units (SI), the unit of exposure is 1 coulomb per kilogram (C/kg), which is therefore equivalent to 3876 roentgens. It must be emphasized that exposure is strictly a measure of the effect of x-ray and gamma ray photons on ***air*** and cannot be directly applied to the x-ray exposure of any other substance. The exposure per unit time, i.e., the exposure rate, is used to describe x-ray machine *output.*

Ionization Chambers

A device for measuring the exposure at some point in the beam is an ionization chamber. An ionization chamber consists of an enclosed volume of air which can be placed at the point of interest, and two collecting electrodes to collect the ion pairs that are released by photon interactions in the air volume. By applying a voltage on the electrodes, the total charge of the ions can be collected and measured. The ratio of the charge collected to the volume of the chamber is proportional to the exposure in roentgens. In addition to measuring the total exposure during some time period (an integrating dosimeter) many dosimeter systems also allow the instantaneous readout of the exposure rate at any time (a dose ratemeter).

Absorbed Dose

The quantity of significance in biological and medical work is not the amount of radiation passing through a point in air, or for that matter, the amount of radiation passing through a point in any substance of interest. Rather, it is the amount of energy absorbed by the substance at that point—the absorbed dose. The absorbed dose is the quantity of primary importance in radiation dosimetry; exposure is often used merely as an indication of the absorbed dose (as the exposure incident on a substance increases, so does the absorbed dose, all other things being equal).

The most commonly used unit of absorbed dose of radiation is the rad, defined as 100 ergs deposited per gram of substance, or 10^{-2} joules per kilogram. Even though 100 ergs per gram is an extremely small energy density(7), it can cause considerable damage to those cells that are directly affected. The rad is a universal unit defined for all ionizing radiations and for all substances. Since the rad is a unit of energy density, if one gram of material received one rad of x irradiation, then one-half of that material received one-half of the energy but the same energy density, namely one rad.

The SI unit of absorbed dose is the gray (Gy), defined as 1 joule per kilogram. One gray is therefore equivalent to 100 rads.

SUMMARY

The properties of x radiation, the production of the x-ray beam, and the various modifers of x-ray beam quantity and quality are topics prerequisite to the informed conduct of radiological examinations. X rays, which are high energy electromagnetic radiations capable of penetrating thicknesses of material, are produced in a polyenergetic spectrum by the collision of high energy electrons on the tungsten target of an x-ray tube. The rate of x-ray production can be altered by the filament voltage which produces changes in the tube current. The quality of the x-ray beam is dependent upon the type of high voltage supply, the accelerating voltage (kVp), and the filtration. The penetrating ability of the beam can be expressed in terms of its half value layer (HVL); its exposure (a measure of the total energy content of the beam) can be measured in roentgens (R); and the energy deposition of the beam (absorbed dose) in any material can be measured in rads. Based upon these fundamentals, the succeeding chapters in this series will investigate the practical aspects of clinical radiology.

REFERENCES AND NOTES

1. The relativistic situation (where, as particulate energy increases, the mass increases) is not a significant phenomenon at the energies utilized in diagnostic radiology.
2. The term "electromagnetic" derives from the physical description of E-M radiation as electrical and magnetic fields which vary both in time and space.
3. $E = h\nu = hc/\lambda$, $c = \lambda\nu$ where E = photon energy (electron volts), λ = wavelength (meters), ν = frequency (cycles/sec), c = speed of light = 3.0×10^8 meters/sec, and h = Planck's constant = 4.1×10^{-15} electron-volt second.
4. In some x-ray machines, special circuits are used to depress these voltage oscillations.
5. Occasionally there are sources of radiation in the x-ray tube other than the focal spot, caused by poorly focused or scattered electrons striking other structures. This radiation is referred to as off-focus or extrafocus radiation.
6. Technically, however, as the mA is increased, the electrical load on the system increases and the kilovoltage may decrease, which will change the energy spectrum.
7. 42×10^6 ergs per gram of water (420,000 rads) will raise its temperature 1 degree centigrade.

LABORATORY EXERCISE 1

X-RAY PRODUCTION AND MACHINE OUTPUT

The output of an x-ray machine is dependent on the accelerating voltage (kVp), the tube current (mA), the exposure time (seconds), and the filtration (mm Al) in the beam. An understanding of the effects of these variables on x-ray output is necessary for the knowledgeable development of specific techniques. A secondary purpose of this exercise is to familiarize the student with the use of an ionization-measuring device.

Equipment

This exercise is to be conducted in the Radiological Health Sciences Learning Laboratory and will require the use of the following apparatus:

Small teaching x-ray machine
Radiation-measuring instrumentation
Assortment of lead diaphragms
Assortment of aluminum filters

Procedure

Center the ionization chamber on the shelf at level 5.

1. Variation of kVp

Exposure parameters:
Filtration — 2.5 mm Al added
Diaphragm — 3 inch diameter

Measure and record the exposure ***rate*** under the following conditions:

Tube Current (mA)	Tube Voltage (kVp)
1.5	110, 90, 70, 50, 30
3.0	110, 90, 70, 50, 30

Plot the data on linear graph paper with x-ray output as a function of kVp.

2. Variation of mA

Exposure parameters:
Filtration — 2.5 mm Al added
Diaphragm — 3 inch diameter

Measure and record the exposure ***rate*** under the following conditions:

Tube Voltage (kVp)	Tube Current (mA)
50	3.0, 2.5, 2.0, 1.5, 1
110	3.0, 2.5, 2.0, 1.5, 1

Plot the data on linear graph paper with the x-ray output as a function of mA.

3. Variation of mAs

The mAs is the product of the tube current and exposure time (mA times seconds = mAs). On many technique charts only the kVp and mAs is given leaving the choice of specific time and current settings to the operator.

Exposure parameters:
Tube voltage — 80 kVp
Filtration — 2.5 mm Al added
Diaphragm — 3 inch diameter

Measure and record the ***total exposure*** delivered in the following situations:

Tube Current (mA)	×	Time (secs)	=	mAs
1		30		30
2		15		30
3		10		30
1		120		120
2		60		120
3		40		120

4. Variation of Filtration

Exposure parameters:
Tube current — 1 mA
Diaphragm — 3 inch diameter

Measure and record the exposure ***rate*** under the following conditions:

Tube Voltage (kVp)	Added Filtration (mm Al)
50	0, 0.5, 1.5, 2.5, 3.5, 6.0
110	0, 0.5, 1.5, 2.5, 3.5, 6.0

NOTE: This machine is equipped with a beryllium window tube and can be considered to have zero inherent filtration; therefore the total filtration in the beam is equal to the added filtration.

Plot the data on semilogarithmic graph paper. (A curve of x-ray output vs. filtration is called an attenuation curve. A straight line on semilogarithmic graph paper indicates that all successive HVL's are equal, i.e., the beam is homogeneous.)

QUESTIONS

1. Express the proportionality between output and the following: kVp; seconds; mA.
2. How does output vary with mAs?
3. A technician has brought you a chest radiograph (100 kVp, 1/2 sec, 20 mA) that is properly exposed but is partially blurred due to diaphragmatic motion. What new parameters would you tell him to use?
4. A radiograph of the elbow (60 kVp, 1/2 sec, 5 mA) has been grossly underexposed and you wish to increase the exposure by a factor of 4. From the relationships determined from your data, what values would you use if you changed only the kVp? the sec? the mA? What disadvantages are there in the three different solutions? How accurate are the three solutions in producing the desired increase?
5. Comment on the accuracy and useful kVp range of this common rule of thumb: "Increase kVp by 10 to double the output."
6. The National Council on Radiation Protection and Measurements (NCRP) recommends that all diagnostic radiographic units operating above 70 kVp have at least 2.5 mm Al equivalent total filtration in the beam. Does this seem reasonable from your data? Why has this recommendation been made?
7. What are the HVL's of the two beams in part 4?
8. If this machine were to be used with 2.5 mm Al total filtration permanently in place, what would be the HVL's of the beams in part 4?

2

RADIOGRAPHIC CONTRAST: SUBJECT CONTRAST

The physical actions involved in the production of a radiograph can be divided into three categories: production of the x-ray beam, interaction of the beam with the object being examined, and the formation of an image for interpretation. The interaction of the beam with the object is the topic of this chapter. The importance of this topic is obvious; the beam-object interaction is the only part of the process in which information about the structure of that object is generated. Once the beam has left the patient, steps can be taken to maximize the visualization of that information, but the information present cannot be increased.

The x-ray beam incident on the patient is reasonably uniform throughout the x-ray field both in the numbers of photons and in the energies of photons. However, in passing through the patient, most of the photons will interact, and only about 5% of the incident photons will emerge unaffected. These remaining photons are then used to form the radiographic image. The radiation field emergent from the patient has localized variations in intensity due to the internal anatomy. For example, far more photons will pass through expanded lungs than will pass through the immediately adjacent vertebral column. These differences in intensity are termed ***subject contrast.***

There are four basic factors that affect the subject contrast: the structure and composition of the subject itself, the kVp, the beam filtration, and the amount of scattered radiation. Variation in these factors will change the overall contrast ultimately displayed in the radiograph. However, changes in ***patient dose*** also go along with changes in any of these factors. In many cases the patient dose can be altered substantially without appreciably altering the information content of the radiograph. For example, reasonable variations in kVp and filtration can be made that will change the radiation exposure to the skin by as much as a factor of five, yet will produce radiographs that are acceptable to most radiologists. It is therefore imperative that every radiologist have a working knowledge of the four factors mentioned above and their effects on subject contrast and patient dose. With this knowledge, he can then decide in his own mind which technique factors are appropriate for every examination.

THE COMPOSITION OF THE SUBJECT AND ITS EFFECT ON SUBJECT CONTRAST: X-RAY INTERACTIONS

It is obvious that a radiograph of two objects of equal thickness and identical material will exhibit no contrast, while unequal thicknesses will show contrast. Likewise, equal thicknesses of dissimilar materials will show contrast, but it is possible to pick appropriate thicknesses of two dissimilar materials so that there will be no contrast between them. Therefore, the contrast in a radiograph is a reflection of the thickness, the density, and the atomic number (which will be discussed later) of the object being radiographed.

The body is made of muscle, fat (which is slightly less dense than muscle), bone, air passages, and compartments with fluid. Therefore, different thicknesses of these components and different combinations of them (one component partially overlying another) will result in a differential absorption across the radiographic field.

One might expect that the film darkening at any point in the radiographic image is inversely related to the total effective tissue mass (an expression taking into account both the ***thickness*** and the ***density*** of the various tissue components) along that x-ray path. Thus, if an air cavity were included, the total effective mass would be reduced and the film darkening would be greater (Fig. 2-1). However, this is only partially true, since all materials do not absorb radiation equally on a gram-for-gram basis. Thus, mass considerations alone are not the sole determinant of the x-ray image of an object.

In the kilovoltage range of diagnostic procedures (30-120 kVp) there are two processes involved in the absorption of photons: the ***photoelectric effect*** and the ***Compton effect***(1). Depending on the energy of a particular photon and the atomic number of the absorbing object, the photon may interact with the object by either the photoelectric or Compton process, or it may penetrate the object without interaction.

The Photoelectric Effect

The photoelectric effect is an interaction between an x-ray photon and an electron tightly ***bound*** to an atom of

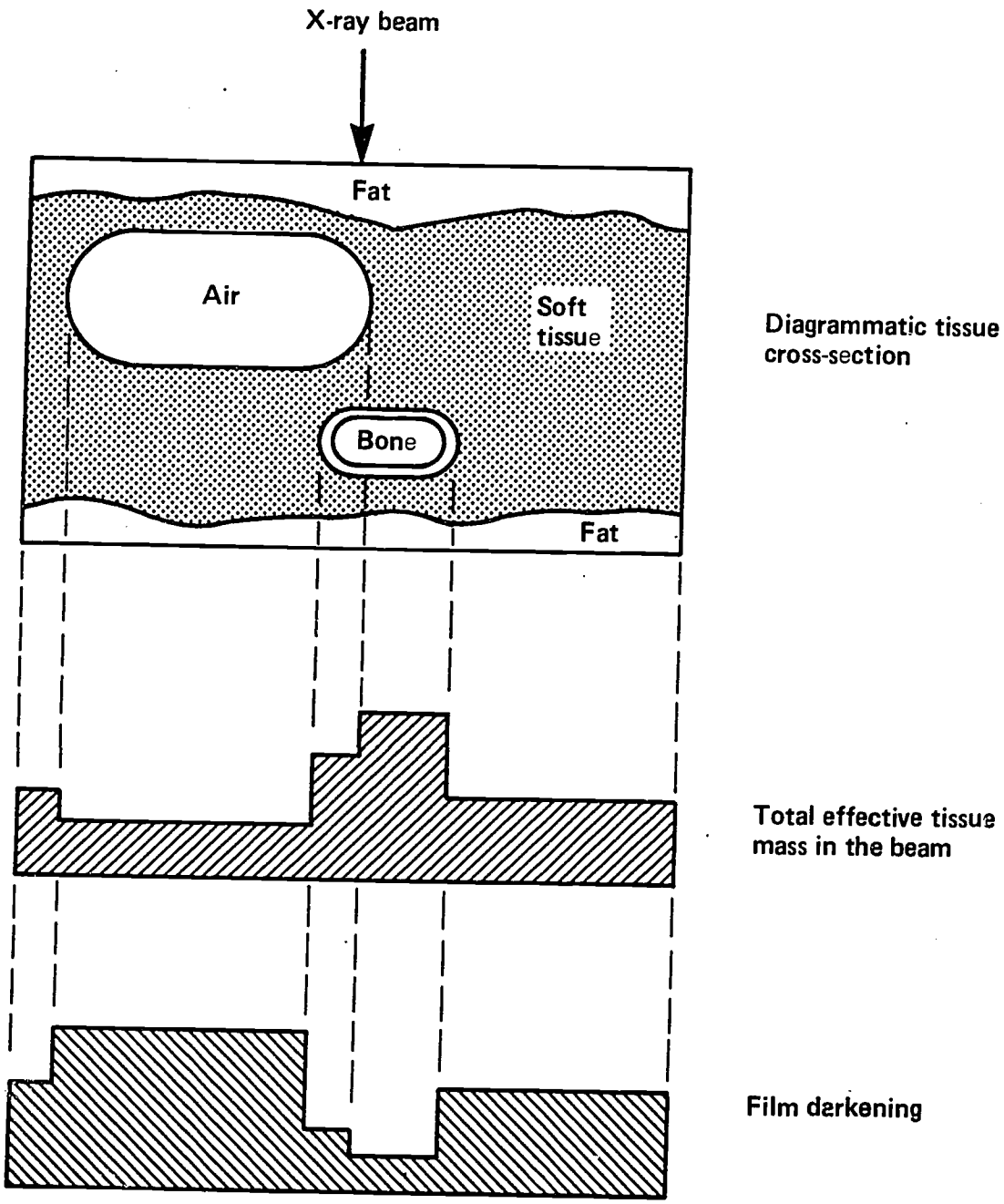


Figure 2-1. Relationship between object mass and film density.

the absorber (Fig. 2-2). (Notice the similarities and differences between Figs. 2-2 and 2-3, and Figs. 1-3 and 1-4.) The total energy of the photon is absorbed and transferred to the electron(2) and the photon therefore ceases to exist. The range of photoelectrons is only a few micrometers so that the photoelectric effect is essentially a local process, with all of the photon energy being transferred to the absorber near the point of interaction. The atom will emit characteristic x rays in filling the vacancy left by the emitted electron; however, the energy of these x rays is very low (for the elements of normal biological tissues) and they too are essentially absorbed locally.

The photoelectric process occurs in a highly selective manner, the probability of absorption being much greater in high ***atomic number*** (Z) materials. (The probability of photoelectric absorption varies approximately as the third power of the atomic number of the absorbing materials.) This accounts for the high efficiency of lead (Z = 82) in absorbing x-ray photons of diagnostic energies. Therefore, if the photoelectric process were the

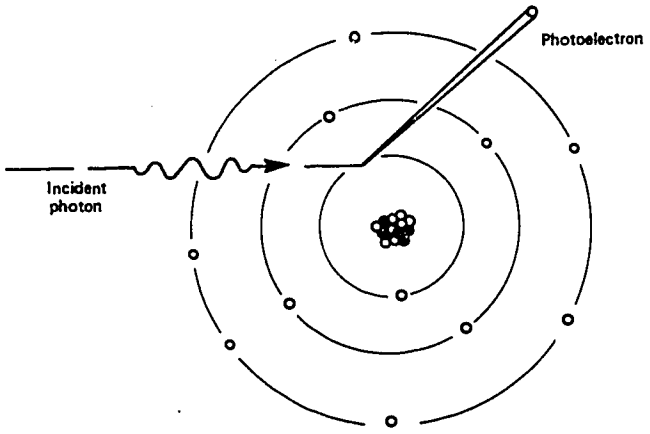


Figure 2-2. The photoelectric effect.

only mode of absorption in biological tissue, bone would be particularly prominent in a radiograph because of its large amount of calcium. The differential photoelectric absorption of bone as compared to an equivalent *mass* of soft tissue is almost 4 to 1. For equivalent *thicknesses* of bone and soft tissue, the differential is about 7 to 1 (because the density of bone is 1.85 gm/cm^3 as compared to 1 gm/cm^3 for soft tissue).

The Compton Effect

The Compton effect, on the other hand, is not a local process. This effect (Fig. 2-3) consists of an interaction between an x-ray photon and a *free* electron (or one very loosely bound to an atom, such as an electron in the outermost energy levels). The law of conservation of momentum (photons carry momentum as well as energy) does not allow the Compton electron to receive the total energy of the incident photon, so the remainder is transferred to a newly created photon. This lower energy photon, called a scattered photon, moves in a different direction than the incident photon, and therefore does not contribute to the formation of the x-ray image (actually it makes a negative contribution to the image which will be discussed later). The probability of Compton interaction is essentially equal for all materials on a gram-for-gram basis. This means that equal thicknesses of different materials absorb x rays by this mode in proportion to their *densities*.

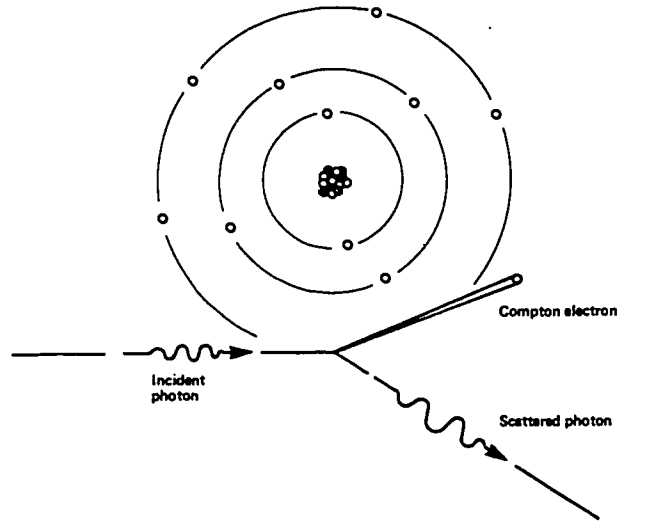


Figure 2-3. The Compton effect.

Thus, if the photons of the x-ray beam depicted in Figure 2-1 would interact in the patient only by the Compton process or pass through unaffected, the subject contrast (intensity variations) of the emergent beam would be inversely related to the effective tissue mass (i.e., if the effective mass increased, the emergent intensity would decrease). However, if the photons would interact only by the photoelectric process or not interact at all, the subject contrast would be inversely related to the effective tissue mass in the beam, but also inversely related to the atomic number of the tissues (i.e., if the atomic number of the tissue increased, the emergent intensity would decrease, assuming the effective mass stayed the same). Since the atomic number and the density of solids are roughly proportional, the effective mass in a vertical section and the atomic number somewhat parallel each other. Therefore photoelectric interactions will result in higher subject contrast than will Compton interactions.

In reality the Compton and photoelectric processes will both occur and contribute to producing a radiograph; the relative percentage of total interactions that occur by one process or the other depends on the energy of the photons (see the Effect of Kilovoltage, below). Therefore, subject contrast does depend on the effective mass composition of the subject and also on the atomic number composition of the subject.

As an aside, two frequently misunderstood terms pertaining to the interaction of radiation with matter are attenuation and absorption. ***Absorption*** of radiation refers to the local deposition of the radiation energy in the object being irradiated. However, when an x-ray beam interacts with an object, not all of the incident energy is absorbed locally — some is emitted as scattered photons as well. Therefore, ***attenuation*** is defined as the reduction in intensity of the x-ray beam as it traverses matter, by either absorption or scattering. Thus absorption refers to the absorption of primary photons and attenuation refers to reduction of the primary beam by *all* interactions.

In general, patient dose is dependent upon the absorption of the beam while the machine exposure factors and darkness of the film are dependent upon the attenuation of the beam by the patient. This is actually a rather loose interpretation of the two terms since a portion of the

patient dose will be due to the absorption of scattered photons, and a portion of the beam reaching the film will consist of scattered photons.

THE EFFECT OF KILOVOLTAGE

As discussed in the previous section, the predominance of photoelectric or Compton interactions will cause higher or lower subject contrast respectively, assuming that the subject is composed of various materials of different atomic numbers. Therefore, to appreciate the effect of kilovoltage on subject contrast, one needs to know the relative amounts of photoelectric and Compton interactions at different photon energies.

At very low photon energies the photoelectric effect is essentially the only interaction process occurring. With increasing keV, the relative importance of the photoelectric process decreases; above 80 keV the Compton effect is essentially the only process occurring(3). The two are of approximately equal importance at about 26 keV, as illustrated in Figure 2-4. The exact shape of this curve depends upon the atomic number of the absorbing material (or the effective atomic number of materials composed of more than one element). This specific figure is the curve for water or muscle, both of which have an effective atomic number (Z_{eff}) of 7.4. Table 2-1 lists the effective atomic numbers and densities of some pertinent materials.

Table 2-1. EFFECTIVE ATOMIC NUMBERS AND DENSITIES

Material	Z_{eff}	Density (gm/cm^3)
Fat	5.92	0.91
Muscle	7.42	1.0
Bone	13.8	1.85
Water	7.42	1.0
Air	7.64	0.00129
Aluminum	13	2.7
Lead	82	11.0

Materials with higher effective atomic numbers yield curves similar to Figure 2-4; however, since the photoelectric process has a higher probability with higher Z materials, the curve will be shifted to the right. The curve for bone is shown in Figure 2-5.

As you recall from Chapter 1, x-ray beams are composed of all photon energies up to some maximum depending upon the "peak" kilovoltage (kVp) supplied to the tube. Thus, any change in the kVp increases the number of photons of all energies; but more importantly, it adds new high energy photons to the spectrum which did not exist in the previous spectrum (shaded areas, Fig. 2-6). These photons have the highest probability of penetrating through the patient to the film and therefore affecting the image. Since these "new" photons are of

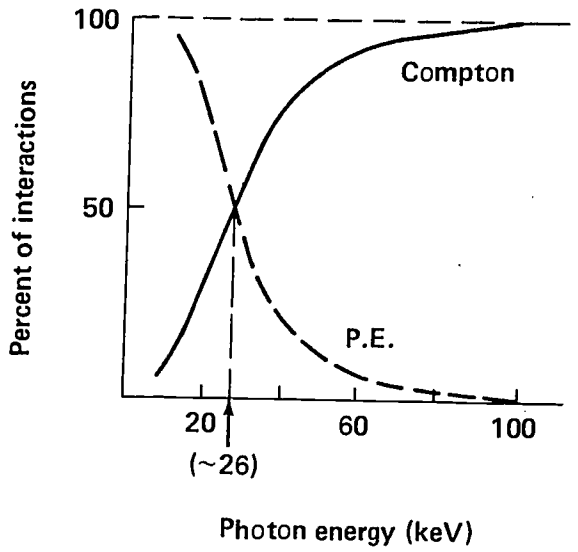


Figure 2-4. Relative percentages of photoelectric and Compton interactions in water.

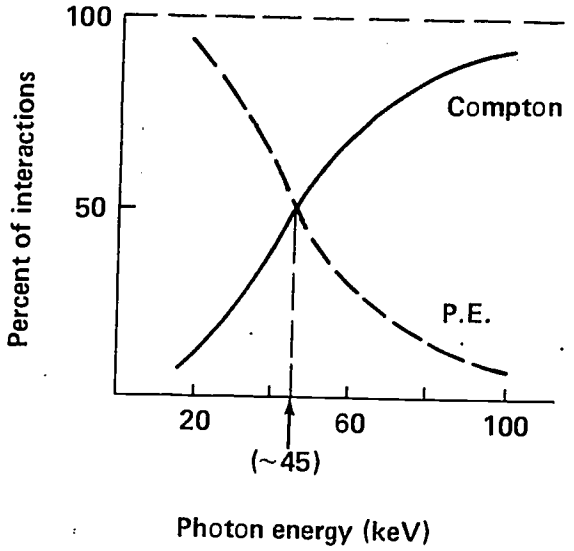


Figure 2-5. Relative percentages of photoelectric and Compton interactions in bone.

higher energy than those of the previous spectrum, the average beam energy is increased and Compton attenuation is increased relative to photoelectric attenuation. The end result is a decrease in contrast because of the lower inherent contrast of Compton attenuation; the subject contrast between equal thicknesses of bone and soft tissue decreases from almost 7 to 1 for photoelectric attenuation to less than 2 to 1 (the ratio of their densities) for Compton attenuation. Although decreasing the kVp of the beam will increase the subject contrast, it will also decrease the overall "penetrating" ability of the beam. Therefore, to allow a sufficient number of photons to reach the film, many more photons must be produced, which ultimately increases the patient dose.

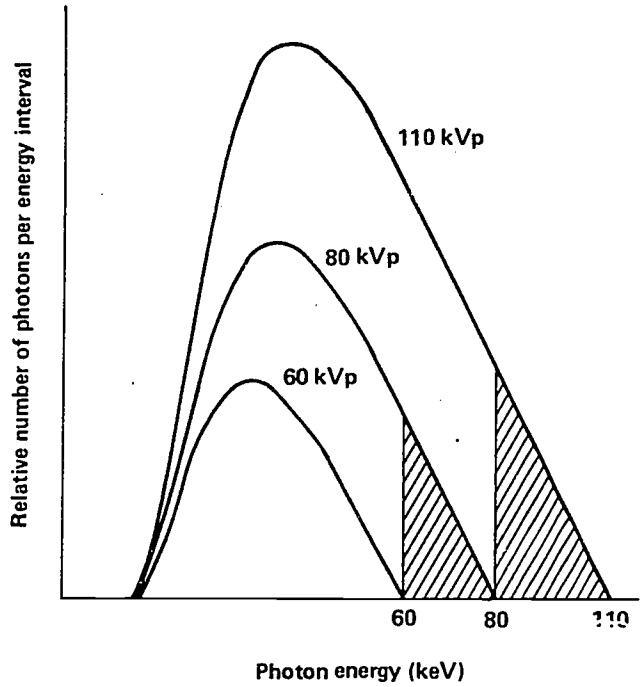


Figure 2-6. The effect of kilovoltage on the photon energy spectrum.

THE EFFECT OF FILTRATION

In a similar manner, the effects of filtration on the beam are best illustrated by the change in the energy spectrum (Fig. 2-7). The inherent filtration in an x-ray tube removes some of the low energy photons; however the spectrum still contains many of these photons. Aluminum is a desirable material for filtration of diagnostic machines because it attenuates mainly by the photoelectric process. It is therefore very efficient at low photon energies and decreases in attenuating efficiency with increasing photon energy. Modest increases in aluminum filtration cause little change in contrast because the low energy photons removed would have contributed little to the image. However, this increase in filtration will yield a marked decrease in patient dose, particularly the entrance skin dose.

The effects of low and high energy photons on contrast and patient doses are illustrated in Table 2-2. This tabulates the percentages of monoenergetic photon beams which pass through 18 centimeters of muscle plus 2 centimeters of either air, lung, fat, muscle, or bone. The increase in contrast with decreasing photon energy is remarkable. With 30 keV photons, 170 times more photons pass through the section with air than through that with bone while at 100 keV the factor is only 1.9 times. However, to achieve this contrast with adequate film darkening would involve a significant increase in patient dose. To obtain equal film densities through the all-muscle section, over 40 times (3.3/.08) the skin dose must be delivered to the patient using 30 keV photons as compared to 100 keV photons!

Table 2-2. TRANSMISSION OF X RAYS THROUGH BIOLOGICAL TISSUES(4)

Tissue Section	Photon Energy (monoenergetic) 30 keV	40 keV	60 keV	100 keV
18 cm muscle + 2 cm air	.17 %	.95%	2.6%	4.7%
18 cm muscle + 2 cm lung	.13 %	.83%	2.3%	4.2%
18 cm muscle + 2 cm fat	.10 %	.63%	1.8%	3.4%
18 cm muscle + 2 cm muscle	.08 %	.57%	1.7%	3.3%
18 cm muscle + 2 cm bone	.001%	.21%	1.1%	2.5%

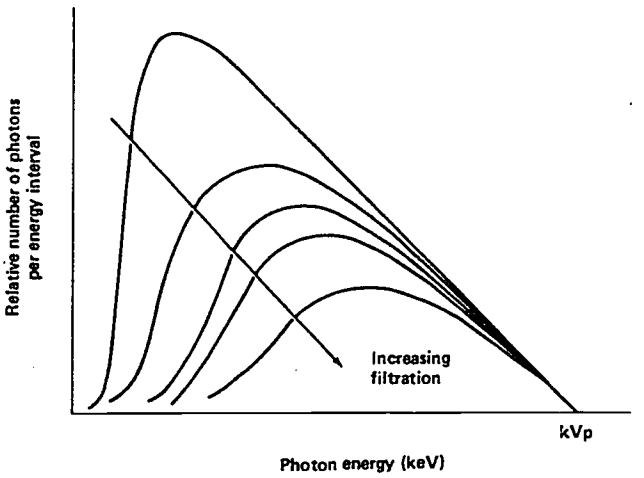


Figure 2-7. The effect of increasing filtration on the photon energy spectrum.

THE PROBLEM OF SCATTERED RADIATION

The scattered photons resulting from the Compton effect cannot be ignored. At the energies involved in diagnostic radiology, scattered photons radiate equally well in all directions. Due to their origin within the object being irradiated, scattered photons are often referred to as *secondary* radiation.

Because of this scattering phenomenon, the object being examined is an undesirable source of radiation. Not only does this radiation create a radiation field in the immediate area, but it also imposes an overall exposure on the x-ray film, partially masking the useful image (Fig. 2-8). The effect of this overlying exposure is to reduce the contrast between gradations in the image, thereby decreasing their visibility. Since scattered radiation is produced as a consequence of the Compton interaction, scattered radiation is another factor contributing

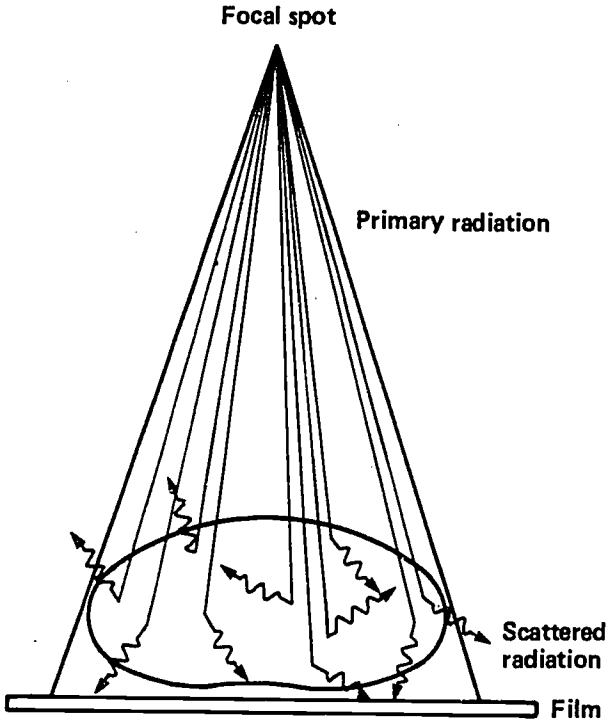


Figure 2-8. Production of scattered radiation in an object.

to the decreased contrast of higher kVp techniques. Besides the patient, other sources of scattered radiation are materials beyond the film plane (the table top or the film holder) which can contribute scatter back to the film. Methods by which scattered radiation are controlled are discussed in Chapter 3.

SUMMARY

The contrast seen on the radiograph (i.e., radiographic contrast as defined by the variations in optical density) is a function both of film and screen characteristics (to be discussed in Chap. 5) and, most importantly, of subject contrast. Subject contrast, i.e., the variations in beam intensity emerging from the subject, is dependent upon the structure and composition of the subject, the kVp, the beam filtration, and the amount of scattered radiation. Each of these contributes to the pattern and energy distribution of information-carrying x rays that expose the film. But also, each of these contributes to the determination of patient dose. Therefore, the appropriate technique factors should only be established after the effects on subject contrast *and* patient dose are considered.

REFERENCES AND NOTES

1. Coherent scattering has been ignored in this exercise because of its negligible contribution to the diagnostic process.
2. A portion of this energy is required to overcome the forces binding the electron to the atom; the remainder appears as kinetic energy of the electron.
3. A useful rule of thumb is that the effective keV is approximately equal to 1/3 kVp for a full or half-wave rectified x-ray generator.
4. Adapted from Ter-Pogossian, M., *The Physical Aspects of Diagnostic Radiology,* Harper and Row, New York, 1967, pp. 171-176.

LABORATORY EXERCISE 2

RADIOGRAPHIC CONTRAST: SUBJECT CONTRAST

The overall radiographic contrast evident in a radiograph is the result of many contributing factors. Radiographic contrast can be subdivided into two categories: subject contrast and film contrast. This laboratory exercise illustrates the effect of the following factors on subject contrast: the composition of the subject itself, the kVp used, the beam filtration, and scattered radiation. Film contrast will be considered in Chapter 5.

Equipment

This exercise is to be conducted in the Radiological Health Sciences Learning Laboratory and will require the use of the following apparatus:

Small teaching x-ray machine
Radiation-measuring instrumentation
Assortment of aluminum filters
Assortment of lead diaphragms
Cassettes with par speed screens
Radiographic film
Radiographic knee phantom
Aluminum stepwedge
Paraffin blocks
Lead numbers

Procedure

1. Effect of the Subject Itself

Make the following anterior-posterior (AP) radiograph of the knee phantom. (AP or PA notation denotes the path of the x-ray beam during exposure; in an AP radiograph, the x-ray tube is on the anterior side of the patient and the film is on the posterior side.) Tape a steel washer, a coin, or some other high atomic number material to the phantom near the knee joint. Be sure that the phantom is not "rocking" back and forth when you expose your film or you will have a good illustration of patient motion on your radiograph.

Exposure parameters:
kVp — 80
mAs — 10
Filtration — 2.5 mm Al added
Diaphragm — 3 inch diameter
Distance — shelf 5
Cassette — 10 × 12 inch, par speed screens

Process the film and examine the contrast and detail of the different materials of the phantom: the "tissue," the bone, and the high atomic number material taped to the phantom. Also notice the effect of the different thicknesses of "tissue" in different portions of the radiograph.

2. Effect of Kilovoltage

Exposure parameters:
Diaphragm — none
Distance — shelf 5
Cassette — 10 × 12 inch, par speed screens

Using constant filtration, make three exposures of the stepwedge on the same sheet of film (in order to eliminate film and processing variations). Shield all of the film that is not under the stepwedge with lead rubber. Be sure to identify the different exposures with lead numbers.

kVp	mAs	Added filtration
50	390	2.5 mm Al
80	9	2.5 mm Al
110	2	2.5 mm Al

Process the film and compare the contrast range in each case.

3. Effect of Filtration

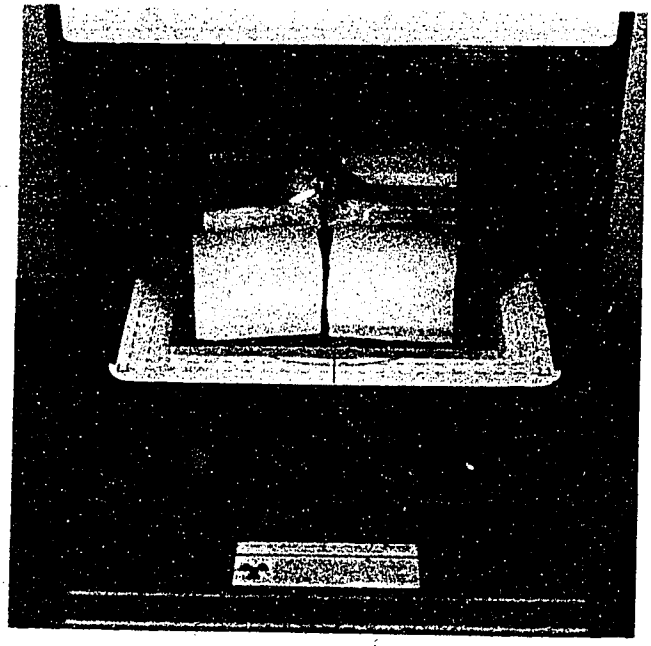
Using a constant kVp and the same exposure parameters as in part 2, make four exposures of the stepwedge on the same sheet of film with varying amounts of filtration.

kVp	mAs	Added filtration
80	7	0 mm Al
80	8	1.5 mm Al
80	9	2.5 mm Al
80	10	3.5 mm Al

Process the film and compare the contrast scale in each case. The total output of the machine is decreased by increasing filtration as evidenced by the increasing mAs required to achieve equal film density.

4. Scattered Radiation

Under the same conditions as part 1, make a second AP exposure of the knee phantom. (Keep the washer or coin in place as before.) Place two stacks of 8 paraffin blocks (about 13 cm in height) on each side of the phantom, just touching it (four stacks of 8 paraffin blocks each). This material will create additional scattered radiation to "fog" the film.



Experimental set-up

Process the film. Examine the contrast and detail of the different materials of the phantom. Compare this film with the one taken in part 1.

5. Clinical Simulation

Use the knee phantom to evaluate the effects of kVp and filtration in a clinical situation.

Exposure parameters:
Diaphragm — 3 inch diameter
Distance — shelf 5
Cassettes — 8 × 10 inch, par speed screens

a. Make the following lateral radiographs of the knee. Be sure to mark the films with lead numbers so that each can be identified.

kVp	mAs	Added filtration
60	13	1.5 mm Al
60	16	2.5 mm Al
60	19	3.5 mm Al
90	2.75	1.5 mm Al
90	3	2.5 mm Al
90	3.5	3.5 mm Al

Compare the six radiographs in terms of detail visibility. Notice that the decreased latitude of the 60 kVp technique results in loss of definition of the boundaries of the phantom.

b. Place the ionization chamber in the exposure cabinet so that it will read the exposure at the skin surface of the knee. Measure and record the integrated total skin exposure delivered by each of these six techniques.

QUESTIONS

1. Which (if any) of the six films in the clinical simulation section would you reject because of poor quality?
2. Considering the radiographic image and also the skin exposure, which radiographic technique do you feel is the best choice for visualizing a hairline fracture?
3. Considering the differing contrast scales, what are the advantages and disadvantages of 50, 80, and 110 kVp?

3

THE CONTROL OF SCATTERED RADIATION

If a radiograph of a large object such as an abdomen were made using conventional techniques, without attempts to control the scattered radiation, the resultant film would have very little contrast and would not yield adequate information about internal structures. If incident photons would either pass through the patient unchanged or be completely absorbed in a single local event (photoelectric effect), then radiographs would consist of sharp, well-defined images (assuming that the other factors involved in radiography are not degrading the image). Unfortunately, in reality, photons may also interact by the Compton process and produce scattered photons which can reach the film and expose it. Since a scattered photon travels in a different direction than the original photon that produced it, it cannot contribute to the radiographic image formed by the direct beam. Instead, it adds to the image's overall background density, thus decreasing contrast. Chapter 3 is concerned with methods of controlling the effects of this undesirable radiation.

SECONDARY RADIATION: SCATTERED RADIATION

The radiation field that emerges from an object being irradiated consists of two distinct parts: primary radiation and secondary radiation. ***Primary radiation*** is the radiation emitted from the x-ray tube. As this primary beam passes through the patient, it is greatly reduced in intensity (attenuated) as its individual photons interact. The number of primary photons that will emerge from the patient at any point in the x-ray field depends on the thickness and composition of the patient along the path between the focal spot and that point. The intensity variations across the x-ray field of the emerging primary beam carry the diagnostic information about the internal structure, and if visualized on film, would yield a good quality radiograph.

Secondary radiation includes any radiation in the beam other than primary radiation. Secondary radiation is a product of the interactions of primary photons. At diagnostic energies, it consists of 1) characteristic x-ray photons and photoelectrons emitted as a result of photoelectric interactions, and 2) scattered photons and Compton electrons emitted as a result of Compton interactions. (The photoelectric and Compton effects were discussed in Chap. 2.) Since electrons have a very short range in tissue, photoelectrons and Compton electrons are essentially absorbed locally. Characteristic x rays from the major constituents of living tissue are of insufficient energy to reach the film. Only when iodine or barium compounds are used as contrast media are characteristic x rays of importance in diagnostic radiology. The characteristic x rays of iodine and barium have energies in the range of 33-37 keV and may reach the film in sufficient numbers to produce a visible effect on the radiograph. In most cases, the only secondary radiation of any significance comes from Compton scattering, which accounts for the general use of the term ***scattered radiation*** rather than secondary radiation. Scattered x rays are emitted in all directions and create a radiaion field around the patient; therefore preventative measures must be taken to reduce their effect on the radiograph and also to protect personnel whose presence may be required in the radiographic room, as for example, during fluoroscopic procedures.

Although a scattered photon from a Compton interaction is lower in energy than its originating photon, the energy spectrum of the scattered field is very similar to the primary beam (but of less intensity) for two reasons. First, the energy loss of diagnostic photons in a Compton interaction is not great; for example, the scattered photon emitted at 90° from the path of a 100 keV incident photon has an energy of 86 keV. With lower energy incident photons, the percentage energy loss is even less. At 30 keV (which is more typical of diagnostic photons since the effective photon energy of the beam is about 1/3 of the kVp) the scattered photon emitted at 90° has an energy of 28.4 keV. Second, considering all of the scattered radiation together as an x-ray beam (of scattered radiation) it is filtered by the tissue through which it must pass. This polyenergetic beam of photons is increased in average energy just as the polyenergetic primary beam is increased in average energy in passing through the aluminum filters in its path. As a final result, the scattered "beam" emitted from the patient is quite similar in energy and penetrating ability to the primary beam emitted from the x-ray machine.

The effect of scattered radiation on the radiograph is serious because it significantly decreases the contrast. The x-ray exposure to the film from scatter is reasonably uniform over the entire field but will produce a much greater change in the optical density of the film in the lightest regions of the radiograph as compared to the darker regions. In such light areas, anatomic details may be obscured or even lost because of this supplemental exposure.

The patient is not the only source of scattered radiation; everything else in the primary beam (filters, collimators, etc.) acts as a source. Scatter from air is negligible because of its very low density; however, materials beyond the film plane (the cassette holder, the table top, the floor or walls) can contribute scatter back towards the film. This is commonly referred to as ***backscatter.*** To reduce the effect of backscatter, a thin sheet of lead is usually built into the back of the cassette or film holder. Lead is used both because of its high density and because at diagnostic energies, lead has a higher probability of photoelectric absorption than of Compton attenuation (therefore relatively few scattered photons are produced, see Chap. 2).

There are three commonly practiced methods of dealing with the scattered radiation from the patient that would normally reach the film. These are 1) restriction of the cross-sectional area of the beam, 2) the use of radiographic grids, and 3) the air gap technique. Each method has its particular advantages and disadvantages and specific instances of applicability.

RESTRICTION OF THE BEAM: COLLIMATION

In every radiological examination, reducing the x-ray field size should be the first consideration in decreasing scatter. This particular method has the added benefit of decreasing the patient dose because of the smaller volume of tissue irradiated. In apparent contradiction to patient dose reduction, the use of a smaller field requires an increase in technique factors in order to obtain radiographs of equal density because of the decreased percentage of scatter contributing to the overall darkening of the film. However, this dose increase is minor compared to the significant patient dose reduction achieved by decreasing the total volume of tissue irradiated.

The effect of beam restriction on the amount of scattered radiation is summarized in Figure 3-1. The relative intensities of primary radiation and scattered radiation reaching the film are plotted as a function of field size. The primary intensity remains constant for all field sizes while the scattered intensity increases markedly with increasing field size. The increase in the amount of scattered radiation is not so dramatic with large fields and the curve reaches a maximum near 1000 square centimeters. Although the total contribution to the film from scattered radiation depends upon the thickness and composition of

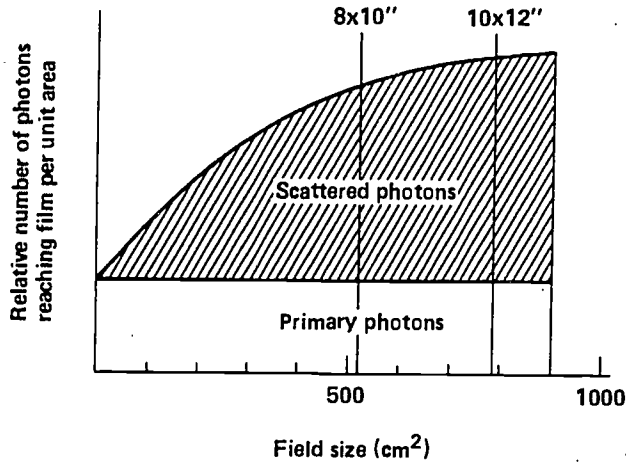


Figure 3-1. Relative number of primary and scattered photons as a function of field size (100 kVp, 30 cm thick object).

the patient and the energy (kVp) of the beam, this idealized curve clearly shows the benefits possible from field limitation.

There are three general categories of devices that can be used to limit the size and shape of the radiation field: diaphragms, cones, and variable collimators.

Diaphragms and Cones

The diaphragm (or aperture diaphragm) is a sheet of lead attached to the tube head with a hole for the x-ray beam. The size and shape of the hole determines the size and shape of the beam. The teaching x-ray machines used in this course use this method of beam restriction. Cones are metal tubes of various sizes and shapes that define and restrict the x-ray field. Cones may be flared or cylindrical; and square, circular, or rectangular. The particular aperture or cone selected is attached to the tube head in a special holder that positions the opening in the center of the x-ray field. Diaphragms and cones are designed to provide a fixed field size and shape at a predetermined distance.

The principal difference between the diaphragm and cone is the point at which the field size is actually determined (Fig. 3-2). The cone limits the field at its far end, away from the tube head, while the aperture limits the field adjacent to the tube head. This distinction is important for the following reason. Since the focal spot is an area of finite size, there is a region at the periphery of the x-ray field that is exposed to radiation from only a portion of the focal spot; this region is called the ***penumbra.*** The production of penumbra results in areas of uneven exposure at the edges of films. For a given focal spot size, the penumbral region decreases in size as the point of beam limitation is moved further from the focal spot; thus the use of a cone will result in less penumbra than the use

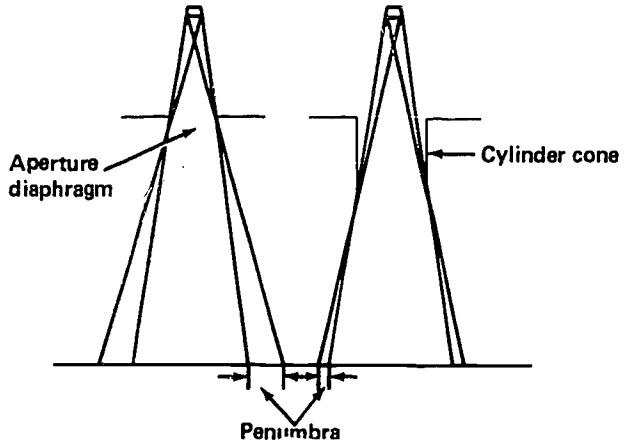


Figure 3-2. Cross-sectional view of an aperture diaphragm and a cone illustrating the effect on penumbra.

of a diaphragm. (Penumbra will be discussed in greater detail in Chap. 6.)

The widespread use of cones as limiting devices has decreased in recent years because of their inherent disadvantages. The primary disadvantage is the limitation of available field sizes, since a different cone is required for every different size and shape field and for every different source-film distance. A common manifestation of this difficulty is the use of a circular cone on film that is rectangular. This has lead to the practice of "cone-cutting," leaving unexposed corners on the film. As shown in Figure 3-3, the smallest field that utilizes the full sheet of film still results in the irradiation of large areas of tissue that cannot be imaged on the film. The other serious drawback of cones has to do with the localization of the radiation field on the patient or cassette. Since the cone rarely extends to the patient, the exact location of the field has to be estimated. In some cases, this leads to missing the area of interest and eventually to the routine use of larger fields than are truly necessary.

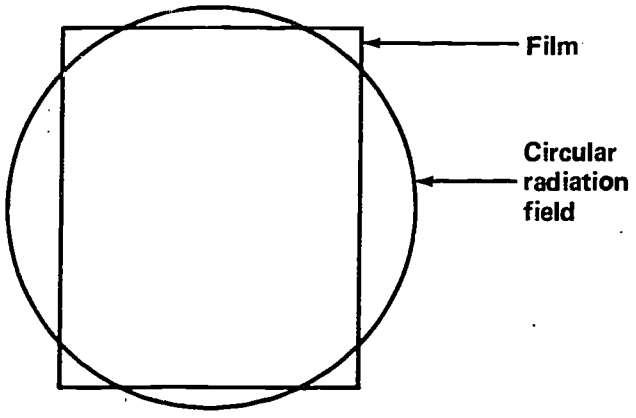


Figure 3-3. "Cone-cutting" with a circular cone and rectangular film.

Variable Collimators

The device presently utilized in nearly every new diagnostic x-ray machine is the variable collimator. The collimator consists of two pairs of independently adjustable lead shutters at right angles to each other which can be used to provide an infinite variety of rectangular (and square) fields (Fig. 3-4). Therefore, in those cases where the entire film must be used, the field can be confined to the film itself without exposing tissue outside of the film area.

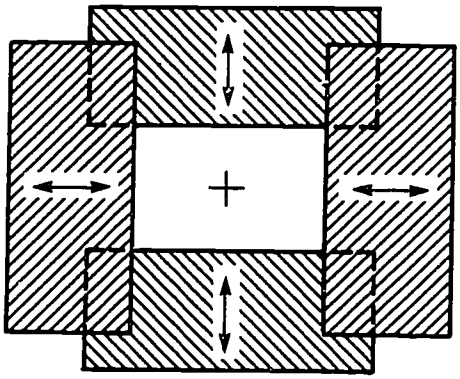


Figure 3-4. Collimator (top view) illustrating adjustable lead shutters.

Another advantage offered by most collimators is a light localizer to indicate the size and location of the x-ray field. A small light is located in the collimator housing at the side of the x-ray beam. The light beam is reflected through the collimator opening by a mirror, as shown in Figure 3-5. The distance between the light bulb and the mirror is equal to that between the x-ray target and the mirror so that the light field is identical to the x-ray field. With the use of the light field, the x-ray field can be effectively collimated to cover only the desired region of the patient.

Most collimators actually have two (or sometimes more) sets of lead shutters which are carefully aligned to move together as a unit. There are two basic reasons for having more than one set of shutters. It is desirable to have the shutters placed as close as possible to the tube head in order to prevent the x-ray beam from striking the internal structure of the collimator and producing additional scattered radiation. This upper set of shutters also serves to minimize the effects of any radiation originating from sources within the tube other than the focal spot (off-focus or extrafocal radiation). However, it is also desirable to have the shutters placed as far as possible from the tube head in order to minimize the size of the penumbra (as discussed previously, increasing the focal-spot to beam-restrictor distance decreases the penumbral size; penumbra and its effect on image sharpness will be discussed in Chap. 6).

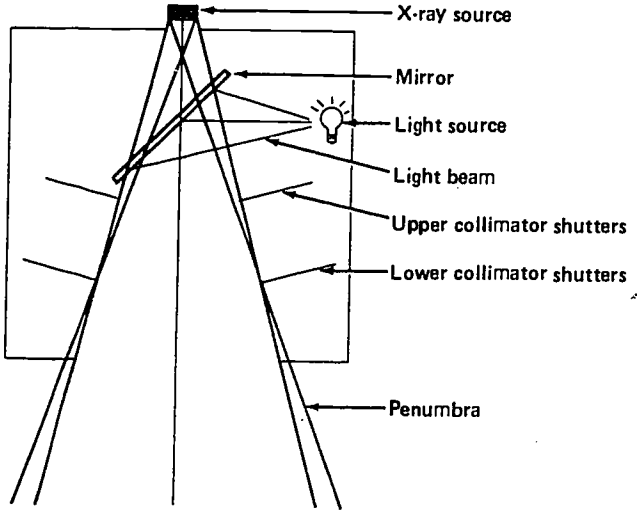


Figure 3-5. Cross-sectional view of a collimator.

Some units provide positive beam limitation (PBL). PBL prevents x-ray exposure unless the beam is collimated to the size of the receptor or smaller. Some PBL systems achieve this by automatic adjustment of the collimators to the full receptor size; others require manual adjustment with interlocks that prevent exposure if the field size is larger than the receptor size.

RADIOGRAPHIC GRIDS

The most effective method of removing scattered photons from a large radiographic field is the use of the radiographic grid, a device placed on top of the film or cassette during an exposure. Grids are constructed of alternate strips of lead and a radiotransparent material, such as plastic, fiber, or aluminum. The strips are oriented in such a way that the primary photons will pass between the lead strips without striking them — much as venetian blinds permit light to pass between them — while the path of scattered photons will strike the lead strips so that they will be absorbed (Fig. 3-6). Unfortunately, the decrease in scattered radiation is not "free," but is achieved only at the expense of increased patient exposure. The lead strips absorb some of the primary photons (those which strike the edges of the lead strips), and the radiotransparent material between the lead strips also absorbs a fraction of the primary beam. The loss of this primary radiation plus the decrease in secondary radiation requires a significant increase in exposure whenever a grid is used, in order to achieve a given film density.

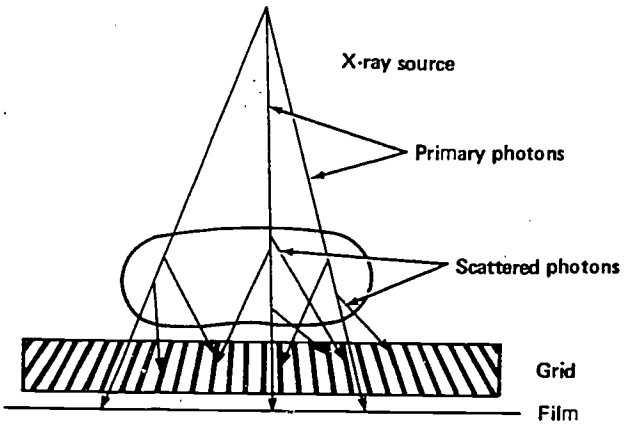
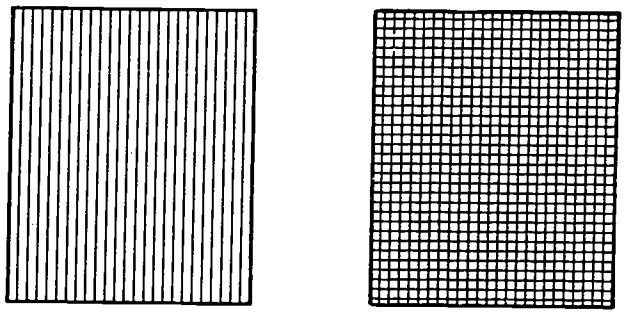


Figure 3-6. Principle of operation of a radiographic grid. Many of the scattered photons will intersect lead strips and be absorbed.

Classification of Grids

Grid Patterns

If one were to look at a grid from above and see the lead strips, the grid pattern could be determined. There are two basic patterns, linear and crossed. In a ***linear grid*** the lead strips when viewed from the top are parallel to each other (Fig. 3-7a). Such a grid will stop photons that are moving at an angle across the grid lines, but not at an angle along the length of the grid lines. A ***crossed grid*** is essentially two linear grids on top of each other, with the grid lines of one perpendicular to the grid lines of the other (Fig. 3-7b). This type of grid will stop photons angled in either direction; however, the alignment of the grid with the x-ray beam is consequently more critical.



a. Linear grid b. Crossed grid

Figure 3-7. Grid patterns (top view).

Focused and Nonfocused Grids

Besides the particular grid pattern, grids are classified as either focused or nonfocused (parallel) grids. The great majority of grids are focused. In a linear ***focused grid,*** the lead strips are oriented so that if the lead strips were all extended, they would meet in a line, called the ***convergent line,*** above the midline of the grid (see the grid cross section depicted in Fig. 3-8a). A focused crossed grid (made up of two focused linear grids at right angles) will have two convergent lines at right angles to each other. The point where they intersect is called the ***convergent point.*** The distance between the grid and

the line or point of intersection is called the *focal distance*. If the focal spot of an x-ray tube is placed along this line or at this point of intersection, the primary transmission through the grid will be essentially equal across the entire area of the grid.

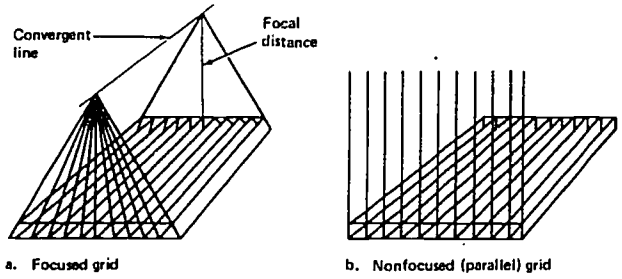


Figure 3-8. Focused and parallel grids. Focused grids have a finite focal distance; the focal distance of parallel grids is infinity.

In a *nonfocused (parallel) grid* the lead strips are all parallel to each other and perpendicular to the face of the grid (Fig. 3-8b). In practice, when a parallel grid is used, the beam will "see" the edges of lead strips in the middle of the grid, but will also "see" portions of the sides of the lead strips at the edges of the grid. In this case, the transmission through the grid will decrease towards the edges of the grid. For this reason, parallel grids are used only for small fields or with very large target-to-film distances.

Grid Ratio

A third factor defining a grid is the grid ratio. The *grid ratio* is defined as the height of the lead strips divided by the width of the interspace material (as illustrated in Fig. 3-9). (The width of the lead strips does not figure in the calculation of the grid ratio.) The grid ratio indicates the *efficiency* of the grid for removal of scattered radiation. In general, grid ratios range from 5:1 to 16:1 for linear grids and from 5:1 to 8:1 for crossed grids. (An 8:1 crossed grid is composed of two 8:1 linear grids and is therefore equivalent in height to a 16:1 linear grid.)

Use of the grid ratio in itself to determine grid efficiency may be misleading, however, because it does not consider the lead thickness. The strip density and lead content together with the grid ratio yields a better indication of the effect of the grid. The *strip density* (expressed in terms of lines per inch) is the number of lead strips per inch of grid. Most grids have strip densities of 60-85 lines/inch. The *lead content* (expressed in mg/cm²) is the total weight of lead per unit area of the face of the grid. These three factors grid ratio, strip density, and lead content, are mutually dependent factors; that is, if one factor is changed, one or both of the others must change. In practice, there are practical limitations to all three factors. Very low grid ratios are not very effective at removing scatter, while the highest grid ratios require significant increases in exposure factors without large improvements in the image. At low strip densities, the grid lines become visibly objectionable, while at high strip densities the lead strips become so thin that they are ineffective in absorbing photons. A very low lead content usually results in too little scatter removal while a very high lead content will significantly decrease the primary beam transmission.

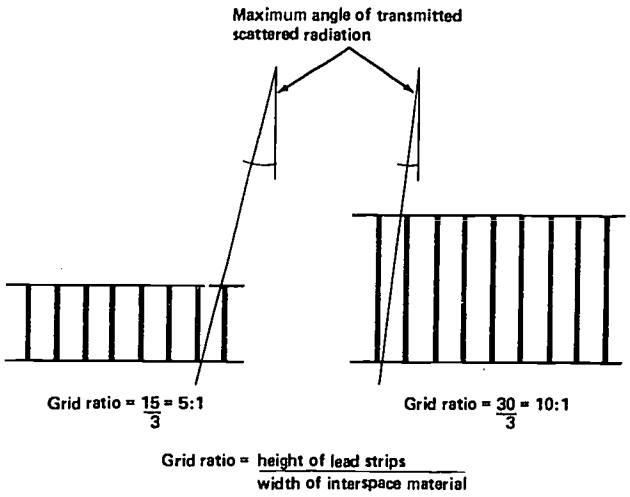


Figure 3-9. Determination of grid ratio. As the grid ratio increases, the maxiumum angle of scattered radiation that can pass through the grid decreases.

Some authors have stated that the lead content of a "well-designed" grid is as good or better an indication of the performance of that grid than the grid ratio. However, this should be expected since the lead content is directly proportional to the grid ratio in grids with equal strip densities. In grids with different strip densities, the visible effect of grid lines on the image must also be considered along with the amount of scatter removed.

Grid Cutoff

The principal difficulty encountered in the use of radiographic grids is grid cutoff due to improper alignment or distance. Focused grids are designed so that when they are used correctly the grid lines are minimized, that is, only the edges of the lead strips are imaged. If the focal spot of the tube is located anywhere along the convergent line of a linear grid, the grid is positioned properly. For a crossed grid to be used correctly, the focal spot must be positioned at the convergent point. Because the linear grid allows the focal spot to be anywhere along a line, a linear grid can be used with tilted tube techniques while a crossed grid cannot.

grid cutoff will occur, as illustrated in Figures 3-10 and 3-11. There will be no cutoff in the center of the field, with cutoff gradually increasing in amount towards the edges of the field. Thus if a line is drawn anywhere across the film, perpendicular to the grid lines, the film density will be maximum at the center and minimum at the edges. The film density will be constant along any line drawn parallel to the grid lines. (For a crossed grid there will be cutoff in both directions since grid lines run in both directions.) Cutoff is slightly greater when the focal spot is too close to the film rather than too far, assuming equal deviations from the correct distance. To help prevent the problem of incorrect source-grid distance, the correct focal range is marked on grids by manufacturers. The *focal range* indicates the range of distances within which the grid can be used. This range varies with grid ratio, being fairly wide for low ratio grids and becoming narrow for high ratio grids.

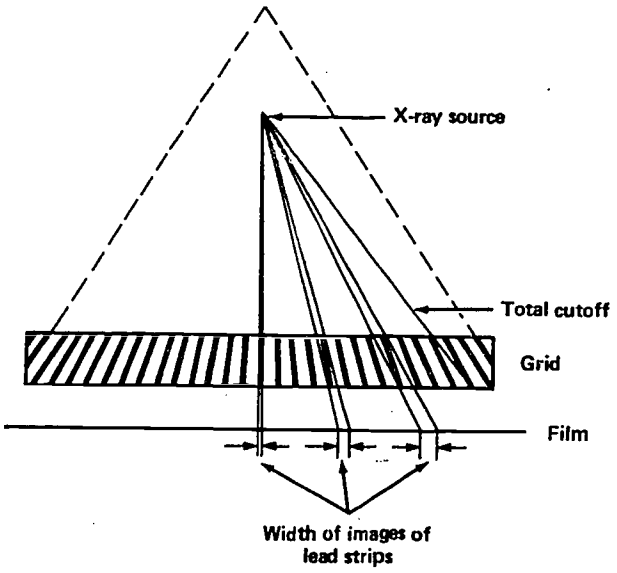


Figure 3-10. Grid cutoff due to the use of a grid at a distance less than the focal distance.

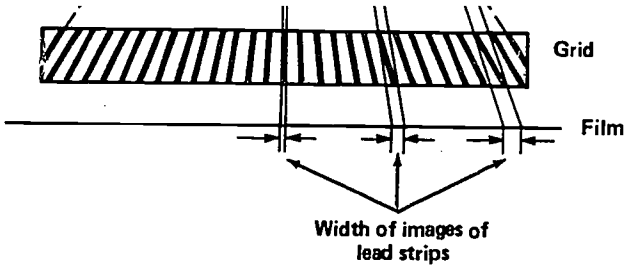


Figure 3-11. Grid cutoff due to the use of a grid at a distance greater than the focal distance.

Theoretically, a parallel grid is always used at an incorrect focal distance because the proper focal distance is infinity. However, the effect is minimal at very large focal distances.

Lateral Displacement of the Grid, and Angulation of the Grid

Lateral displacement of a grid and angulation of a grid are essentially the same problem; the focal spot is located laterally to the convergent line, but at the correct focal distance. As illustrated in Figure 3-12, all of the lead strips are misaligned with the beam and cutoff will be uniform and across the entire film. The resultant film is too light and the defect will probably be attributed to incorrect exposure factors. As a consequence lateral displacement and angulation of grids is not commonly thought to be a problem in clinical practice. However, if this occurs, there is obviously a substantial amount of unnecessary patient exposure (due both to the film retake and the increased exposure factor used for the retake). To assist in the proper positioning of linear grids, they are marked

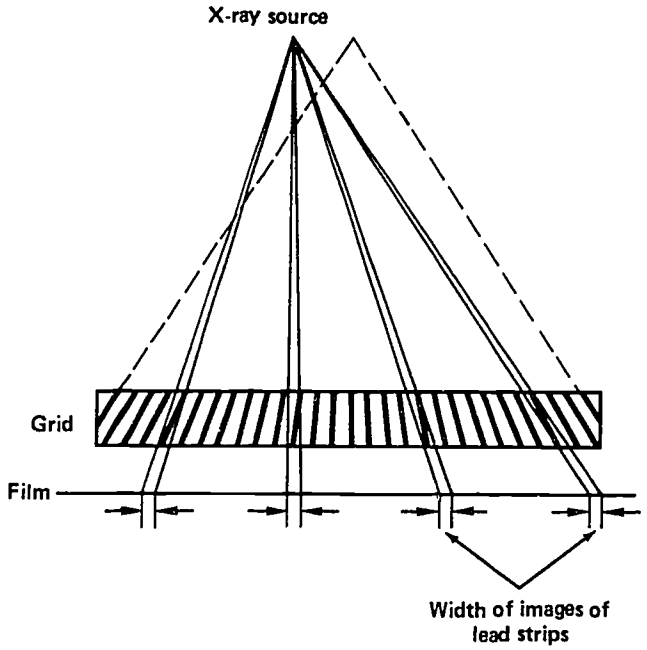


Figure 3-12. Grid cutoff on the lateral displacement of a grid. A slight angulation of the x-ray tube or grid (across the grid lines) produces essentially the same situation.

with a line that indicates the midpoint of the grid pattern. The convergent line is located perpendicularly above this line. Crossed grids are marked with two perpendicular lines, the point of intersection indicating the centerpoint (corresponding to the convergent point) of the grid pattern.

Linear grids will allow lateral displacement or angulation parallel to the grid lines so long as the focal spot remains on the convergent line. Therefore, linear grids can be used for tilted tube techniques. However, unless the angulation is small, cutoff may be encountered. If the tube head is moved in an arc (to maintain a constant source-film distance) the perpendicular tube-grid distance will decrease. Therefore the tube head will be below the convergent line and cutoff will occur. This is illustrated in Figure 3-13.

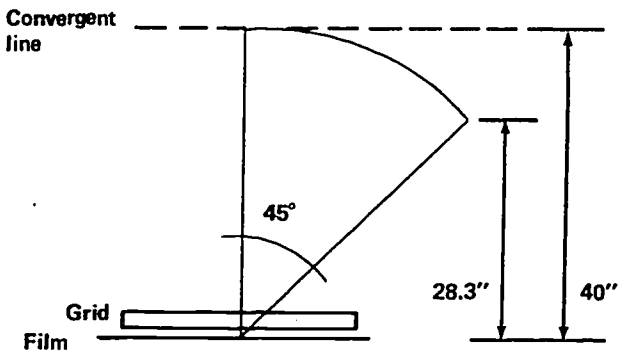


Figure 3-13. Linear grids can be used with tilted tube techniques (if tilted along the grid lines). However, at large angles the *vertical* source-grid distance will decrease, leading to cutoff, unless the source-to-film distance is increased appropriately.

Upside-down Grid

If a focused grid is used upside down, only the central portion of the beam will remain unaffected and severe cutoff will be experienced laterally (Fig. 3-14). The resultant radiograph will have an image only in a strip down the middle of the film with no exposure on either side. (A crossed grid will result in only a small square of exposure in the middle of the film.) The top or tube side of the grid carries the manufacturer's markings (grid ratio, lines per inch, focal range, and the centerline or centerpoint markings).

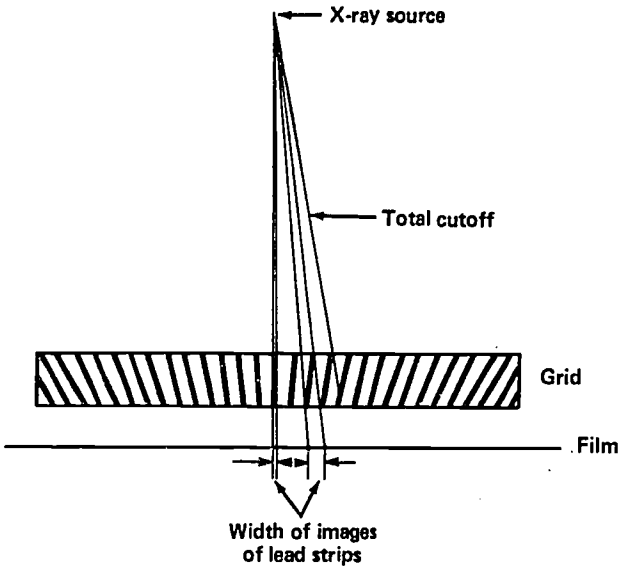


Figure 3-14. Grid cutoff caused by an upside down focused grid.

In actual practice, more than one of the conditions producing grid cutoff may occur simultaneously and will result in slightly different radiographic patterns. For example, if the grid is displaced laterally and also used at the incorrect focal distance, the film will be light on one side and dark on the other. The particular side of the film that is darkest with relation to the side of the lateral displacement depends on whether the distance was greater than or less than the focal distance (Figs. 3-15 and 3-16).

Moving Grids

The moving grid was developed in order to remove the images of the lead strips, which were particularly objectionable with early coarse grids, from the radiograph. Moving grids, called Potter-Bucky grids or just Buckys(1), are usually reciprocating, continuously moving back and forth through a range of a few centimeters. The movement must be nonsynchronous with the x-ray pulses from

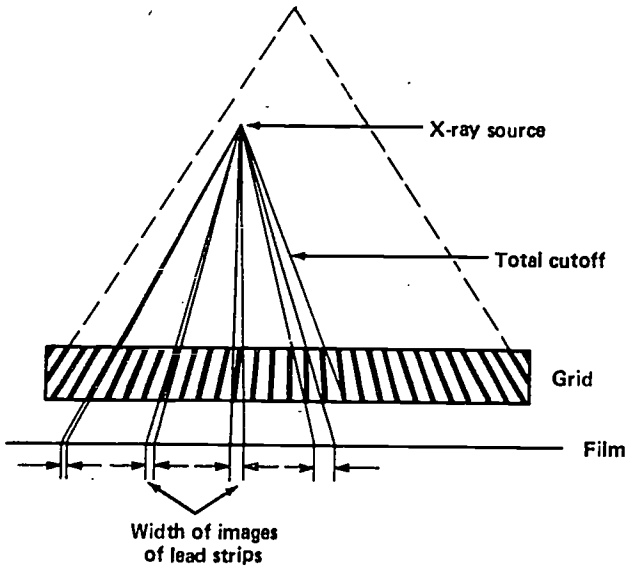


Figure 3-15. Grid cutoff caused by a combination of lateral displacement and decreased source-grid distance.

the x-ray generator so that the grid lines are not superimposed upon previous ones, which would leave visible grid lines or variations in density related to the grid lines. A serious disadvantage of the Potter-Bucky grid is that the patient exposure must be somewhat increased, primarily because the lateral displacement of the grid during its movement results in slight grid cutoff. Also, the mechanism which moves the grid could cause vibration of the image receptor, producing a blurred image and therefore causing an unnecessary retake examination. With the high quality grids that are presently manufactured, grid lines are not distracting and stationary grids could be utilized in far more examinations than at present.

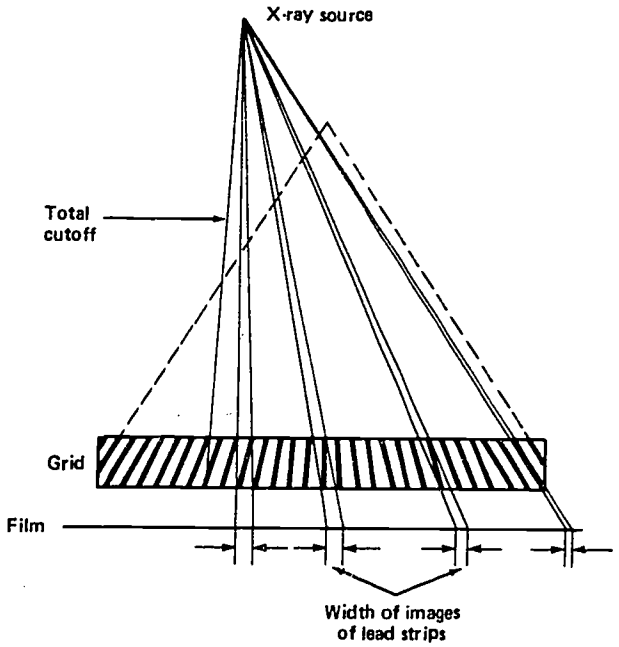


Figure 3-16. Grid cutoff caused by a combination of lateral displacement and increased source-grid distance.

Choosing the Appropriate Grid

There is no simple "rule of thumb" for choosing the appropriate grid in any given situation; a compromise is always involved. The "price" one must pay for the increase in radiographic contrast is a large increase in patient exposure. The improvement in the radiograph must be evaluated against this price. Table 3-1 shows some average figures by which the mAs must be ***multiplied*** when changing from a nongrid to a grid technique. These numbers are approximate because they do not take into account the exact thickness and composition of the subject or the strip density of the grid being used, but they serve to illustrate the point that grids should only be used when necessary, and that the lowest acceptable grid ratio should be employed.

Table 3-1. GRID EXPOSURE FACTORS(2)

$$\frac{\text{mAs with grid}}{\text{mAs without grid}}$$

Grid Ratio	At 60 kVp	At 85 kVp	At 110 kVp
No Grid	1	1	1
5:1	3	3	3
8:1	3.75	4	4.25
12:1	4.75	5.5	6.25
16:1	5.75	6.75	8
5:1 Crossed Grid	4.75	5.5	6.25
8:1 Crossed Grid	6.75	7.5	9

At diagnostic x-ray energies, scattered photons are emitted in all directions. However, with increasing kVp, the percentage of the scatter emitted in the forward direction increases. Therefore, higher ratio grids, which allow a smaller angle of scattered photons to be transmitted (see Fig. 3-9) are needed. Usually 8:1 grids give good results below 90 kVp, while a 10:1 or 12:1 grid is recommended at higher energies. In addition to the increased forward scatter, a high kVp produces a greater amount of total scatter relative to the primary radiation. Therefore, the exposure factors given in Table 3-1 increase with increasing kVp for all grids. Table 3-1 assumes that the necessary increase in exposure is made by increasing mAs while keeping kVp constant. However, some departments will increase exposure by kVp increases. This approach, however, will affect image contrast and therefore may possibly also affect the choice of grid.

It should be obvious from the preceding discussion that although radiographic grids are effective in removing

Table 3-2. SUGGESTED CRITERIA FOR GRID RATIO SELECTION(3)

Grid Ratio and Type	Relative Clean-up	Positioning Latitude	Preferred kVp	Relative Patient Exposure
5:1 Linear	Low	Wide	Below 80	Very low
8:1 Linear	Medium	Moderate	Below 90	Low
10:1 Linear	High	Restricted	Below 110	Medium
16:1 Linear	Very high	Almost none	Above 100	High
5:1 Crossed*	High	Wide	Below 100	High
8:1 Crossed*	Very high	Restricted	Up to 125	Very high

*Cannot be used with tilted tube techniques

scattered radiation, they do increase patient exposure and require accurate positioning. The use of grids in standard techniques should be evaluated with patient exposure in mind. Grids should not be used when not necessary, for example with thin body parts. In all cases the lowest ratio grid that yields adequate films should be used. Table 3-2 provides some insight into the common use of various grids.

AIR GAP TECHNIQUE

Another method of reducing the amount of scattered radiation that reaches the film is by use of the air gap technique. This involves separating the object being examined and the film by a distance (creating an "air gap") as opposed to having them as close to each other as possible. As shown in Figure 3-17, many of the scattered photons that would reach the film in position A will miss the film entirely if the film were in position B. This method is most effective at low kVp's. At high kVp's a greater proportion of the scatter is in the forward direction and will reach the film even with an air gap. By way of comparison, a 12-inch air gap corresponds approximately to a 8:1 grid, depending on the specific physical parameters of the examination.

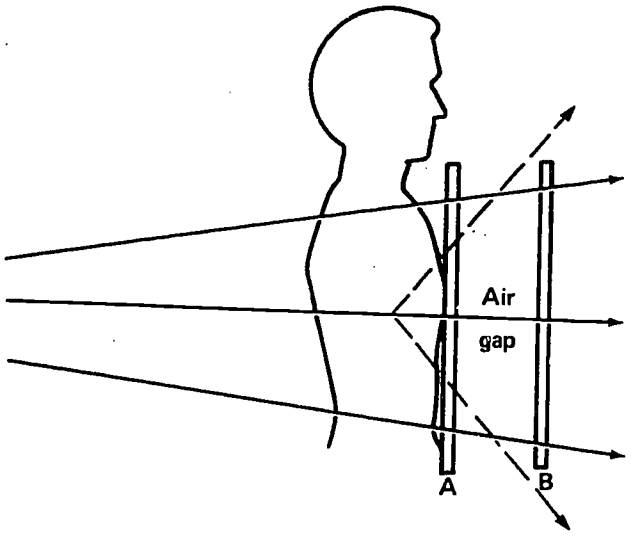


Figure 3-17. Air gap technique.

Significant problems with the air gap technique are 1) magnification of the image, 2) loss of detail because of increased penumbra, and 3) a slight increase in patient exposure since the patient is relatively closer to the source. In order to decrease the magnitude of these problems, source-film distances of 6 to 10 feet are generally used. The most common application of this method is for chest radiography of large or obese patients.

SUMMARY

The degradation of a radiographic image by scattered radiation is a serious problem. When a very thick body section is radiographed, the intensity of scattered radiation reaching the film may be larger than the intensity of the primary radiation. The simplest and least costly way to decrease the percentage of scatter is to reduce the x-ray field size to the minimum required for the information desired. This has the added benefit of decreasing the total radiation exposure of the patient. The most effective method of decreasing scatter, however, is by the use of radiographic grids. Since the use of grids does result in large increases in patient exposure, the lowest acceptable grid ratio should always be used and special efforts should be taken to avoid "grid cutoff" problems. Even with the use of a grid, the field size should be minimized, so that the volume of tissue irradiated is as small as possible. Finally, the "air gap" technique is an effective method to reduce scatter, but only in special situations. It is generally used with chest radiographs performed at large source-film distances.

REFERENCES AND NOTES

1. Dr. Gustave Bucky invented the radiographic grid and Dr. Hollis Potter invented the moving grid. It is therefore unusual that only the moving grid has retained either name, that of Dr. Bucky.
2. Table taken from *Characteristics and Applications of X-ray Grids,* Liebel-Flarsheim Company, Cincinnati, Ohio, 1968.
3. *Ibid.*

LABORATORY EXERCISE 3

THE CONTROL OF SCATTERED RADIATION

All objects being radiographed produce scattered radiation which may cause an overall "fogging" of the radiographic image. The primary methods of reducing this scattered radiation are collimation, the use of grids, and the air gap technique. This laboratory exercise investigates the effect of scattered radiation on a radiograph and illustrates the methods of minimizing the consequences.

Equipment

This exercise is to be conducted in the Radiological Health Sciences Learning Laboratory and will require the use of the following apparatus:

Small teaching x-ray machine
Assortment of lead diaphragms
Assortment of aluminum filters
Radiographic pelvis phantom plus wood supports
Cassettes with par speed screens
Radiographic film
Assortment of x-ray grids

Procedure

1. Collimation

Exposure parameters:
kVp — 80
Filtration — 2.5 mm Al
Distance — shelf 6
Cassette — 10 × 12 inch, par speed screens

Place the wood supports on the shelf against the sides of the exposure cabinet. Position the pelvis phantom across the exposure cabinet on these supports for a PA view (as shown in the following figure). The cassettes and grids can then be placed underneath the phantom without having to move it.

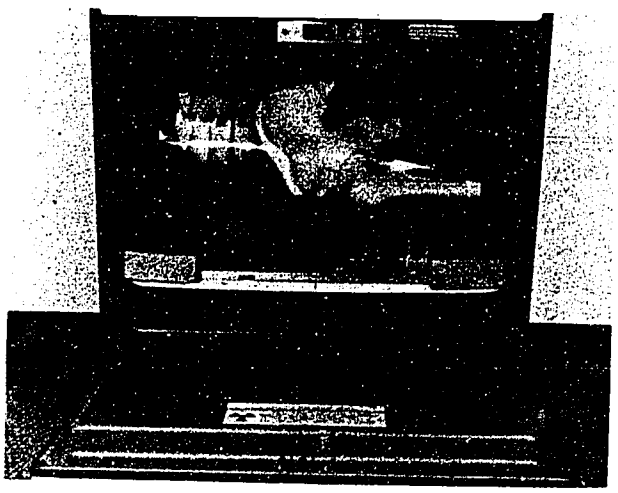
Make the following three radiographs:

Diaphragm	mAs
none	36
3 inch diameter	42
1 inch diameter	150

Process the films and compare the detail visibility in the three radiographs.

2. Radiographic Grids

a. Using a constant field size and the same exposure parameters as in part 1, make the following radiographs:



Experimental set-up

Grid	Diaphragm	mAs
6:1 linear	3 inch diameter	270
12:1 linear	3 inch diameter	450
6:1 crossed	3 inch diameter	585

b. Again using the same exposure parameters as in part 1, make the following radiographs which illustrate various types of grid cutoff:

Grid	Diaphragm	mAs	Conditions
12:1 linear	none	450	Grid upside down
12:1 linear	none	450	Grid tilted along grid lines
12:1 linear	none	450	Grid tilted across grid lines
12:1 linear	none	110	Distance of 22 inches* (shelf 3)

*In the last case (distance of 22 inches) move the phantom, grid, and the film to shelf 3. (Actually all of the films will have some grid cutoff because of too large a focus-grid distance. Unfortunately, the size of the pelvis phantom forces this situation; the distance to shelf 6 is about 45 inches, rather than the conventional technique distance of 40 inches. However, the cutoff is not too great under these conditions.)

c. Lateral positioning of the grids is quite critical, particularly with high ratio grids. To illustrate the magnitude of this effect, make several exposures of a grid without an object in the beam on one piece of film with various amounts of lateral displacement. With a 10 × 12 inch grid with the convergent line running between the front and rear of the exposure cabinet, make exposures with lateral displacements of 0, 1, 2, 3, and 4 inches. Actually the grid will probably hit the side of the cabinet with slightly less than 4 inches of displacement. Record that distance and make the exposure there. Shield all of the film except a strip across the shorter dimension of the film. Then strips of successively increasing lateral displacement can be demonstrated on a single sheet of film. Use the following exposure conditions:

kVp — 80
mAs — 4
Grid — 12:1 linear
Filtration — 2.5 mm Al added
Distance — shelf 5
Diaphragm — none
No subject in the beam

3. Air Gap Technique

Place the phantom on the floor of the upper cabinet, without a shelf. Use the film (no grid) at shelf 6. Using the same exposure parameters as in part 1 make the following radiograph:

Diaphragm	mAs
none	75

Compare the detail visible in this film with the other films. It should be evident that the air gap is not used under these conditions: a thick, solid body part and short source—image receptor distance.

QUESTIONS

1. If you had to decide between the three grids used in this exercise, which one would you use for pelvic radiography? Why?
2. Why is the air gap technique not used clinically at an SID of 40 inches as in this exercise?
3. If a crossed grid is used upside down, what will be the pattern of the cutoff?

4

INTENSIFYING SCREENS

The previous chapters have been concerned with the formation of a useful x-ray beam and the modification of that beam as it passes through the patient. After the beam emerges from the patient it contains radiographic information about the internal structure plus some interference in the form of scattered photons. Methods of dealing with this scattered radiation were discussed in Chapter 3.

The radiographic information contained in the emergent beam exists as variations in x-ray intensities across the radiographic field. These variations must then be converted into a visible image. The visualization of this information can be enhanced or degraded by the choice and design of the imaging equipment, or by the methods used to reduce scattered radiation, but the total information content carried by the emergent beam cannot be increased without changing the exposure factors. As an example, the distinction between fat and soft tissue is relatively difficult to detect radiographically; with normal techniques the intensity variations in the emergent x-ray beam may be minor. However, at very low kVp's, as in mammography, the emergent beam will contain variations related to the amounts of fat and soft tissue. In the first case essentially no distinction may be possible, no matter how refined the detection system is. In the second case (kVp < 40) the distinction can be made, although with an inappropriate detection system, that distinction might be lost.

In the Introduction the radiographic contrast was said to depend on two independent factors — subject contrast and film contrast (see Fig. 0-1). The distinction between the two should now be readily apparent. ***Subject contrast*** is expressed by the intensity variations in the beam emergent from the patient. It is affected by machine factors which alter the spectrum of the x-ray beam, and by physical factors which describe the size and composition of the object being radiographed. ***Film contrast*** increases (or decreases) the subject contrast by converting the x-ray intensity variations into visible images, resulting in the overall radiographic contrast of the radiograph.

The choice of the term "film contrast" is not entirely appropriate since film is not always involved in radiographic imaging. In addition, other variables involved in producing the resultant image, such as the use of intensifying screens and film processing factors, are all lumped under the term film contrast. Therefore, a better choice of terms might have been "imaging system contrast." However, since "film contrast" is generally accepted, it will be used in this lecture series but the broader meaning of the term should be kept in mind. The next two chapters investigate the most common imaging system used in radiology — radiographic film used in conjunction with intensifying screens.

THE PURPOSE OF INTENSIFYING SCREENS

If ordinary photographic film is placed in a lighttight container, the film can be exposed to x rays and an image can be obtained by developing the film. In the early days of radiology this was the standard procedure. Since x-ray photons have a much greater range than light photons, the single thin emulsion used on photographic film is not very efficient for x-ray absorption. Most of the x rays simply pass through the film without interaction with the emulsion (i.e., without exposing it). Direct x-ray films are now designed with two thick emulsions so that a significantly greater proportion of the photons will be stopped. Yet, even with present radiographic film, less than 5% of the incident photons are absorbed by the film and contribute to the image.

An ingenious method to ***increase the efficiency*** of radiographic image formation was developed after the discovery of x-ray fluorescent materials(1). Certain inorganic salts emit light photons when exposed to x radiation(2). If a piece of photographic film is placed between two layers of such a material and then exposed to x rays, a large portion of the darkening of the film will be a result of the light emission from the fluorescent material rather than from the x rays themselves. The increase in efficiency of this system over the direct exposure of photographic film allows a significant ***decrease in patient exposure***. There are three reasons for this greater efficiency: 1) there are more total materials (screens ***plus*** film) to absorb radiation; 2) the atomic numbers of the materials in screens are higher and therefore more effective in absorbing radiation than the materials in the film; and 3) film responds more efficiently to light photons than to x-ray photons. The use of fluorescent materials, in so-called ***intensifying screens,*** in

conjunction with radiographic film accounts for the great majority of radiographs, although there are some cases where the higher patient exposure of a nonscreen method is used. The design and use of particular types of x-ray films will be discussed in the next chapter.

A typical film-screen imaging system consists of a double emulsion x-ray film sandwiched between two intensifying screens. The film and screens are mounted inside a cassette, a lighttight case that keeps the film and screens in intimate contact. Photons from the incident radiation beam may be 1) absorbed in either intensifying screen which emits fluorescent light which exposes the film, 2) absorbed in the film itself, or 3) pass through without interaction. Although there will always be some interactions in the film itself, an average 90-95% of the film exposure in an intensifying screen system will be caused by the light photons emitted from the screens.

CONSTRUCTION OF SCREENS

A typical intensifying screen is made up of three layers: a base material, the fluorescent layer, and a protective coating (Fig. 4-1). The *base* is either cardboard or plastic and is used to provide support for the fluorescent material; it must be uniformly radiotransparent and free of any metal or other foreign materials which could be imaged on the film. It must also prevent moisture from reaching the fluorescent salt. In the case of cardboard base materials, the back surface is coated to seal out moisture.

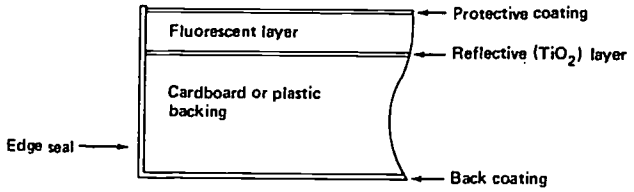


Figure 4-1. Cross-section of an intensifying screen.

The *fluorescent layer* consists of crystals of the fluorescent compound suspended in a flexible binder material. The compound used in most intensifying screens has been calcium tungstate, although barium lead sulphate and barium strontium sulfate were used by some manufacturers to produce their higher speed screens. The more recent "rare earth" intensifying screens use gadolinium, lanthanum, or yttrium oxysulfides, lanthanum oxybromide, barium fluorochloride, or various combinations of these compounds. The fluorescent compound must be extremely pure and uniform in crystal size, mixed uniformly with the binder, and coated evenly on the base. The binder itself must be clear in order to minimize the absorption of the emitted light. To retain as much of this light as possible, a thin reflective layer of titanium dioxide is coated on the screen base underneath the fluorescent layer.

A *protective coating* of hard plastic is necessary to hinder the inevitable deterioration of the screen. This layer prevents damage from the abrasion of dust particles and film during loading and unloading operations; prevents damage from moisture; helps decrease the buildup of static electricity; and provides a surface that can be easily cleaned. A similar layer is provided around the edges of the screen to prevent entry of moisture in that region.

The screens are mounted in pairs inside of film cassettes, one on each leaf. The purpose of the cassette is to hold the film and intensifying screens in intimate contact and also to provide protection from light and physical abuse. The front surface of the cassette is made of a radiolucent material such as bakelite, magnesium, or aluminum, to minimize the absorption of the x-ray beam. The cassette back, however, is intentionally designed to absorb the beam by the addition of a thin sheet of lead. This significantly reduces the amount of backscatter that can reach the film and obscure the image (see Chap. 3).

SCREEN SPEED

The primary motivation for utilizing intensifying screens is to take advantage of the exposure reduction which they allow. In general, radiographs made with intensifying screens will require from 1% to 10% of the exposure needed for a nonscreen exposure.

There are two commonly used methods of quantitatively comparing different film-screen combinations: *screen speed* and *exposure* required for a given optical density (usually 1.0 over base plus fog). Since intensifying screens are quite energy dependent, i.e. their exposure reduction varies with kVp, these two parameters are usually expressed as relative values compared to an average speed calcium tungstate screen.

The speed or exposure value of a particular x-ray screen system can be varied by the choice of specific construction details. The choice of these details is not a trivial matter, because the specific construction directly affects the radiographic detail that can be visualized by that screen.

Calcium tungstate screens are usually categorized into four speed categories: slow, medium, fast, and very fast. Unfortunately, the names of screens have not been conventionalized by manufacturers and there are many different terms in use. These names are listed in Table 4-1.

A similar problem exists in the absolute speed of intensifying screens obtained from different manufacturers. The exact construction details (see the section on Intensifying Screen Resolution, below) and therefore the relative speed of screens with the same nominal speed will vary between manufacturers. Consequently, speed

Table 4-1: RELATIVE EXPOSURES REQUIRED FOR VARIOUS CALCIUM TUNGSTATE INTENSIFYING SCREENS

TYPE	SLOW	MEDIUM	FAST	VERY FAST
NAMES	Detail Ultra-detail High definition High resolution	Par Average Regular Standard Mid speed	High speed	Super high speed High-plus Ultra speed
RELATIVE EXPOSURE	4 to 2	1	.5	.35

variations of up to a factor of three have been reported between calcium tungstate screens labeled medium speed(3). Clearly a mixture of different screens in a department could cause a serious reproducibility problem.

The speed of a screen is basically a function of the amount of light emitted when the screen is exposed to a given level of x radiation. The light output of a screen (and its speed) can be increased by using more efficient fluorescent materials (such as the rare earth compounds), by increasing the thickness of the fluorescent layer, and/or by increasing the size of the fluorescent crystals. However, since speed and resolution are inversely related to one another (at least for various screens of the same chemical composition), an increase in screen speed will decrease the resolution capability of the screen.

RARE EARTH INTENSIFYING SCREEN SYSTEMS

The chain of events that occur in a film-screen system is graphically depicted in Figure 4-2. A number (N) of x-ray photons emerge from the patient and reach the intensifying screen. Some fraction (P) of these will interact with the screen and produce L light photons. These light photons will interact with the film resulting in a latent image that will develop to a density of D optical density units.

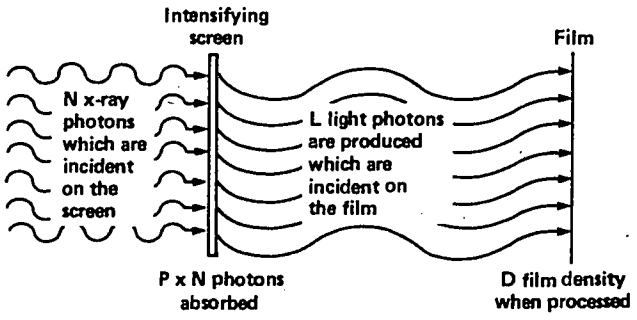


Figure 4-2. Diagrammatic representation of a film-screen system.

There are three basic ways of increasing the overall *speed* of the system(4):

1. Modify the intensifying screen to absorb a greater fraction (P) of the incident photons.
2. Modify the intensifying screen to produce more light photons (L) from the same number of photons (P x N) absorbed.
3. Modify the film so that fewer light photons (L) are needed to produce a density of D.

The rare earth screen systems achieve increases in speed by methods 1 and 2; that is, the rare earth compounds are more efficient than calcium tungstate in converting x-ray photons into light photons. In fact, the rare earth compounds are so efficient that some of the speed increase can be sacrificed by using a slower film (requiring more light photons, L, to produce a given film density). This is done in order to minimize the effect of quantum mottle or noise (discussed in the next section).

Table 4-2 provides an intercomparison of some of the available rare earth screens, along with the required exposures relative to a medium speed calcium tungstate screen. It is important to emphasize the word "relative" since the speed varies differently with kilovoltage depending upon the composition of the screen.

INTENSIFYING SCREEN RESOLUTION

As mentioned in the previous section, the gain in speed achieved by rare earth screens (as compared to calcium tungstate screens) is accomplished by increasing the percentage of x-ray photons absorbed and/or increasing the amount of light emitted after absorption of an x-ray photon. However, there are also methods of modifying the construction of intensifying screens which alters their relative speeds. These generalized design concepts are utilized in producing the four categories of calcium tungstate screens mentioned above (see Screen Speed), and are also exploited in rare earth screen design. However, the "price" which must be paid for any increases in film-screen system speed is a decrease in resolution.

Factors Affecting Intensifying Screen Speed and Resolution

Thickness of Fluorescent Layer

As mentioned previously, a thicker phosphor layer will result in a faster screen because it will absorb more x-ray photons and produce more light than a thin layer. How-

Table 4-2: COMPARISON OF VARIOUS RARE EARTH INTENSIFYING SCREENS WITH A MEDIUM SPEED CALCIUM TUNGSTATE SCREEN(5)

VENDOR	SCREEN	COMPOSITION	SPECTRAL EMISSION	FILM	RELATIVE EXPOSURE AT 70 kVp
Eastman Kodak	Lanex	Gadolinium and lanthanum oxy-sulfide	Green	Ortho G	0.29
E.I. DuPont	Quanta II	Barium fluoro-chloride	Blue	Cronex 4	0.25
	Quanta II			Cronex 7	0.5
General Electric Company	Blue Max 1	Lanthanum oxy-bromide	Blue	Cronex 4	0.4
	Blue Max 2		Blue	Cronex 4	0.25
3M Company	Alpha 4	Gadolinium and lanthanum oxy-sulfide	Green	XD	0.5
	Alpha 4			XM	0.25
	Alpha 8		Green	XD	0.25
	Alpha 8			XM	0.125
U.S. Radium	Rarex B	Yttrium oxysulfide	Blue	Cronex 4	0.25
	Rarex BG	Gadolinium and yttrium oxysulfide	Blue	Cronex 4	0.25
For Comparison	Medium speed	Calcium tungstate	Blue	Cronex 4	1.0

ever, the detail will be less because of the greater *diffusion* of the light in the thicker screen. There is less light diffusion in a thin screen because the light photons are produced closer to the film. As shown in Figure 4-3, the light emitted from the fluoroscent crystals will reach a larger area of film in a thick screen than in a thin one, and therefore will create an image significantly larger than the original beam of radiation.

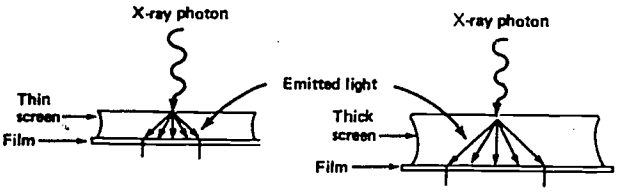


Figure 4-3. Diffusion of emitted screen light and its effect on detail. Light paths with an angle greater than 45° have been arbitrarily ignored in this simple drawing.

Size of Fluorescent Crystals

A second factor affecting the speed of screens is the size of individual fluorescent crystals. A larger crystal will emit more light than a smaller one. Although this factor is often overrated, a size increase does increase the screen speed somewhat, but it also decreases the resolution by diffusing the borders of the image (Fig. 4-4).

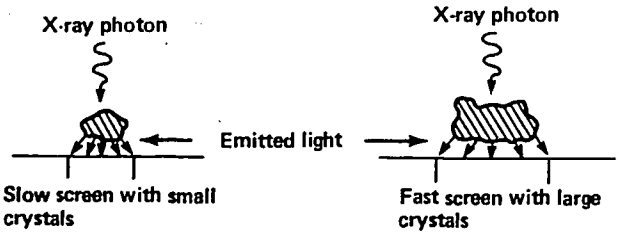


Figure 4-4. Effect of crystal size on detail.

Use of Light-absorbing Dye

A commonly used method of increasing the resolution (and decreasing the speed) of an intensifying screen is the addition of light-absorbing dye to the fluorescent layer. The shortest path for the light photons to travel from one of the crystals to the film is along the line perpendicular to the film-screen surface (see again Fig. 4-3). The path length increases for those paths that are oblique to the film-screen surface. The light photons that reach the film along the longer paths are more detrimental to the image because they reach the film at a greater lateral distance from the incident x-ray photon as compared to those light photons traveling shorter paths. The addition of light-absorbing dye to the screen will reduce the total light output from the screen, but the most detrimental photons will be selectively decreased because their longer path length increases their likelihood of absorption.

In practice, all of these factors are employed to produce slow or fast screens. The fastest screens are thicker and are composed of larger crystals. The slowest screens (with highest resolution) are thinner, have smaller crystals, and may have a yellow or pink dye added to the fluorescent layer. Therefore, it is difficult to evaluate these individual factors other than by a theoretical discussion.

The resolution of a film-screen combination can be summarized by examining Figure 4-5. If an x-ray beam is incident upon a cassette that is partially covered by a lead block, the image of the edge will not be as sharp as the actual edge of the block. The diffusion of light under the edge of the lead block results in a gradual change in the film darkening, rather than the idealized abrupt change; the faster the screen the greater the light diffusion and the more gradual this change.

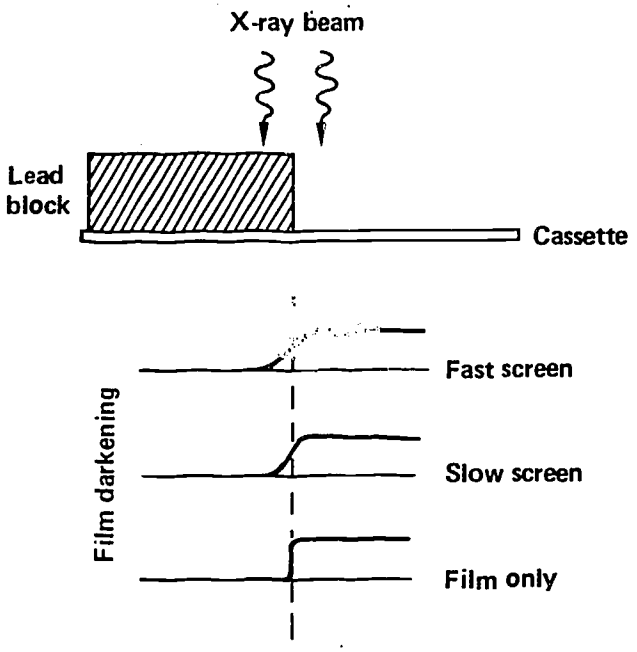


Figure 4-5. Border response of film-screen and film imaging systems.

It is important to note the distinction between the potential detail resolution provided by the imaging system and the actual overall detail visibility of a radiograph (as presented in Fig. 0-1 of the Introduction). The detail visibility in a radiograph is dependent upon many factors, some of which are focal spot size, magnification, motion, amount of scattered radiation, effectiveness of scattered radiation removal, choice of film, and choice of intensifying screen. The intensifying screen will place a limit on the detail resolution that can be imaged (and this limit generally is inversely related to screen speed); however, the detail limit imposed by the screen may not be the major factor in determining the overall detail that can be visualized in any given situation.

Factors Affecting Imaging System Resolution: Radiographic Mottle(6)

The term resolution has been used in the previous discussion without any attempt at defining it. The resolution (or resolving power) of intensifying screens is measured by the detectability of "line pairs." A *line pair* (LP) is defined as one line plus one space; a resolution of one line pair per mm means that lines 1/2 mm wide separated by 1/2 mm spaces can be detected. Typical resolution values for different calcium tungstate screens range from 5-8 LP/mm for fast screens, 8-10 LP/mm for medium screens, and 10-15 LP/mm for slow screens. Ultimately, resolution is limited by the resolving ability of the human eye; there are some indications that the eye cannot resolve more than 10 LP/mm under normal viewing conditions and distances without using magnification methods.

A significant factor in the total resolution of an imaging system is the penumbra, which will be discussed in Chapter 7. However, there is another factor that *interferes* with the resolution of a film-screen imaging system.

A radiograph that is obtained by exposing a film-screen combination to a uniform field of radiation will exhibit an irregular mottled pattern. This uneven appearance is called *radiographic mottle* and has been attributed to three different phenomena: quantum mottle, structure mottle, and film graininess, as diagrammed in Figure 4-6.

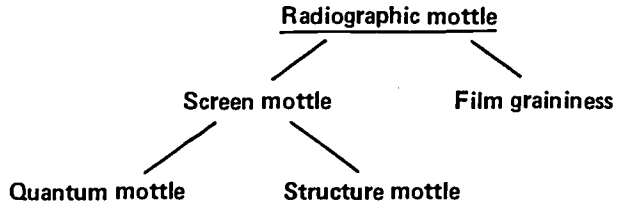


Figure 4-6. The components of radiographic mottle.

Film graininess is a result of the size of individual silver halide crystals and their tendency toward clumping during development (see Chap. 5). Film graininess is only visible under magnification; its contribution to overall mottle is negligible. ***Structure mottle*** has to do with physical variations in the structure of the intensifying screen, usually phosphor composition or thickness, as previously discussed. The high quality of modern screens has minimized the effect of structure mottle, which can be shown by making two identical films with visible mottle using the same screen. If the mottle were caused by variations in the structure of the screen, the pattern would be identical on the two films and could be visualized by overlaying the two films. This is not the case.

The most significant cause of radiographic mottle is quantum mottle. *Quantum mottle* (or *noise)* is a result of the statistical fluctuation in the number of photons (quanta of energy — hence the term quantum mottle) incident upon any given area of the intensifying screen. If the average number of photons per mm^2 is n, the standard deviation is $\sqrt{n}$ (i.e., in 68% of all cases, the number of photons falling in any mm^2 will be $n \pm \sqrt{n}$). Therefore, if n = 100 then one standard deviation is equal to $\sqrt{100}$ = 10 or 10% of n. For larger values of n, such as 10,000 or 1,000,000, the standard deviation is a smaller percentage, 1% or 0.1%, of the number itself. Therefore, as the number of photons necessary to produce an image is decreased by using faster films and faster screens, the statistical fluctuation of the number of photons will increase, causing an increase in quantum mottle.

A dramatic example of the effect of quantum mottle or noise was given by Albert Rose(7). He simulated photographic images by successively increasing the total number of photons used in creating the images (Fig. 4-7). Each succeeding image uses about five to ten times the number of photons as the preceding one; as more light photons are used, the quantum mottle decreases.

Radiographic mottle is not often identified on radiographs but is detrimental because it imposes a *limit of resolution.* Small objects with sizes on the order of the mottle may have reduced visibility, particularly objects that have low subject contrasts. This loss of resolution can only be decreased by using a greater number of photons for the examination, that is by using a "slower" detection system.

One other cause of a mottled radiograph is improper film processing. This abnormal pattern, *processing mottle,* is more visible than radiographic mottle because the size of the pattern is much larger. Film processing will be discussed in Chapter 5.

Picture	Number of photons	High-light brightness, foot-lamberts
a	3×10^3	10^{-6}
b	1.2×10^4	4×10^{-6}
c	9.3×10^4	3×10^{-5}
d	7.6×10^5	2.5×10^{-4}
e	3.6×10^6	1.2×10^{-3}
f	2.8×10^7	9.5×10^{-3}

Figure 4-7. Simulated images illustrating the effect of quantum mottle on image resolution.

FILM-SCREEN MATCHING

Although it has always been important to match the appropriate film with the intensifying screen being used, the advent of rare earth intensifying screens has made this imperative. Calcium tungstate screens emit light in the blue region of the spectrum with a peak at about 430 nanometers. Radiographic film was specifically designed to be most sensitive to that portion of the spectrum. The fluorescence of lanthanum and gadolinium oxysulfide "rare earth screens" is in the green region of the spectrum, with a peak at 545 nanometers. Films to be used with these screens are therefore designed to take advantage of this green light (see Table 4-2). Consequently, for optimal performance, it is imperative that the appropriate film always be used in conjunction with the specific intensifying screen.

In addition, it should be noted that in adding rare earth imaging systems to an existing department, the safelights will have to be evaluated. Some safelights that are "safe" for blue sensitive film will fog films that are green sensitive (see Chap. 5).

INTENSIFYING SCREEN ARTIFACTS

One of the serious difficulties encountered with the use of intensifying screens is the production of artifacts. A radiographic artifact is defined as any abnormal appearance on the film that is the result of improper storage, handling, or processing of the x-ray imaging system. (Only artifacts pertinent to intensifying screens will be discussed here. Others will be discussed in the next chapter.) The most significant problem leading to screen-induced artifacts is poor film-screen contact. Screens must be kept in intimate contact with the film over the entire area. For this reason cassettes are constructed

require reasonable care in handling if they are to perform satisfactorily. They should be checked regularly for poor contact, and immediately after one is abused in a manner that might have caused damage.

The presence of dust, dirt, hair, or any other small foreign bodies within the cassette is a significant problem on three counts. First, these foreign objects will shield the film from the fluorescent light and cast a shadow onto the film. These shadows detract from the overall image and in some cases could be confused as foreign bodies or abnormalities within the patient. The second problem is abrasion caused by the action of these small objects between the screen and film during loading and unloading procedures. Such abrasion will eventually wear through the protective coating and lead to deterioration of the screen. And finally, dirty screens may cause poor film-screen contact. To minimize the problems arising from dirty screens, special care should be taken to keep the darkroom as clean as possible. In addition, the cassettes should be cleaned on a regular basis with appropriate screen cleaners.

An additional problem that may occur is the abnormal staining or discoloration of screens. Stains may appear in localized regions as a result of accidental spills of a foreign substance, or they may be a uniform discoloration across the screen which occurs as the screen ages. Some, but not all, screens darken with age and assume a slight beige hue. Any stain or darkening will result in decreased light output. Therefore, if a screen assumes a hue with age, its speed will slowly decrease. For this reason, screens could be periodically evaluated for speed. This is particularly important whenever new screens are purchased. If there are speed differences between equivalent screens used in the department, reproducible films will not be produced during routine examinations.

design criteria are different, screen film is less efficient than nonscreen film for direct exposures and consequently requires greater exposure — both to the film and to the patient. However, some manufacturers have developed 90-second processable direct exposure film which requires less exposure than the direct exposure of screen film.

The direct x-ray exposure of any radiographic film will produce a lower contrast image (but with significantly higher maximum density) than the images produced using a film-screen system. This difference in contrast can be attributed to differences in film response to x radiation and light. Because of the higher dose usually involved in nonscreen techniques, careful consideration must be given to nonscreen examinations. As a particular example, the laboratory exercise associated with this chapter will consider the case of radiography of the hand and will compare nonscreen vs. screen techniques. Some points to be considered:

1. Theoretically there should be far greater detail visible with a nonscreen technique. However, the other factors affecting detail visibility, particularly penumbra and the reduced contrast of direct exposure, may reduce this difference.
2. There may be artifacts produced on a screen-technique radiograph that could possibly interfere with a diagnosis, particularly when a foreign body decision is involved.
3. The higher contrast of a screen technique could lead to films that are overexposed at the fingertips and underexposed at the wrist. One solution to this problem is the use of higher kVp for the screen exposure, resulting in a lower contrast film. The exact kVp and the overall "grayness" desired can be determined experimentally.
4. The patient exposure decreases with increasing speed of the detection system.

SUMMARY

As is true in so many questions that arise in radiological practice, there are no definite answers as to what screen should be used in any situation. Since patient exposure and screen resolution are inversely related, each physician must decide for himself what level of detail loss is acceptable in the interests of lower patient dose and in consideration of the other factors involved. With the continual improvement in the design and manufacture of intensifying screens since the earliest days of radiology, the general trend has been towards faster, more efficient screens.

REFERENCES AND NOTES

1. Actually x rays were discovered when Wilhelm Roentgen noticed that a screen of barium platinocyanide crystals glowed (fluoresced) when a Crookes tube was energized.
2. There are two terms pertaining to light emis substance after x-ray exposure, fluoresc phosphorescence. The distinction betwee lies in the time interval between x-ray stimu light emission. If the time interval is less seconds, the phenomenon is called "fluore i' s greater than 10^{-8} seconds, it is called " escence."
3. Thompson, Thomas T., Rare earth film/sci binations. *First Image Receptor Conferer Screen Combinations,* U. S. Department Education, and Welfare, Public Health Ser and Drug Administration, HEW Publicati 77-8003, October 1976, p. 118.
4. Shaffer, Edward C., Limiting factors in radic the chest. *Ibid.,* p. 101.
5. Adapted from Thompson, Thomas T., op 119-120.
6. This section is based on the assumption th adequate contrast for visualization.
7. Rose, Albert, *Vision: Human and Electronic* Press, New York, 1973, p. 38.

LABORATORY EXERCISE 4

INTENSIFYING SCREENS

Nearly all radiographs are presently made using an intensifying screen-film imaging system because of the smaller quantity of radiation that is necessary to produce the image. However, this dose reduction is only achieved by a sacrifice in the detail that can be visualized by that system. Therefore, the screen appropriate for any given examination must be determined by the detail required for that examination.

Equipment

This exercise is to be conducted in the Radiological Health Sciences Learning Laboratory and will require the use of the following apparatus:

Small teaching x-ray machine
Assortment of aluminum filters
Assortment of lead diaphragms
Cardboard exposure holders
Various speed intensifying screens
Radiographic film
Radiographic hand phantom
Radiographic knee phantom
Brass or copper wire mesh

Procedure

1. Detail Visualization

Exposure parameters:
kVP — 60
Filtration — 2.5 mm Al added
Diaphragm — 3 inch diameter
Distance — shelf 5

Make the following exposures of the phantom hand:

Intensifying Screen	mAs
Detail	24
Par speed	6
High speed	3
Very high speed	2.1
Cardboard film holder	100

Compare the detail visible in each of the radiographs. Also, note the general densities of the radiographs. (The factors were chosen according to the manufacturer's relative screen speeds and should yield almost equivalent film densities. Therefore, a light radiograph indicates that the speed of the screen is not as great as the manufacturer's claim.)

2. Rare Earth Intensifying Screens

If you have rare-earth intensifying screens (and the appropriate film) available in your department, make additional exposures of the phantom hand using those screens. Use the same exposure parameters as in part 1, and modify the mAs to produce the proper exposure. Compare these films with the films from part 1 in terms of detail and patient exposure.

3. Contrast

Some people have objected to the use of intensifying screens for radiographs of extremities because of the higher contrast of the screen system. (The films from part 1 show this difference in contrast.) One solution is to use a higher kVp when using a screen in order to decrease the contrast. This has the added benefit of decreasing the patient dose. (These topics were discussed in Exercise 2.) Using the ***detail*** screen and the same exposure parameters as in part 1, make two additional exposures of the phantom hand with the following higher kVp techniques:

kVp	mAs
90	4
100	2

4. Poor Film-screen Contact

Intimate contact between the film and both intensifying screens is necessary to achieve good detail visualization. Using the damaged cassette, make the following exposures:

a. Determine the speed of the damaged cassette and make a radiograph of the phantom hand as in part 1.

b. To determine the areas of poor screen contact, make a radiograph of a brass or copper wire mesh using the following exposure parameters:
kVp — 45
Filtration — 2.5 mm Al added
Diaphragm — none
Distance — shelf 5

Use 20 mAs for a par speed screen. Other screens will take more or less exposure, depending upon their speed relative to a par speed screen.

5. Film-screen Matching

If you have rare-earth intensifying screens available, make an exposure with rare-earth screens and conventional film and another with par speed calcium tungstate screens and rare-earth film. Use the exposure parameters from part 1 and the mAs appropriate for the intensifying screens being used. Compare these films with those from parts 1 and 2.

QUESTIONS

1. From an examination of the radiographs of the hand phantom and their relative exposures, what screen/nonscreen would you employ for extremity radiography, spot filming, and general radiographic work? Why?
2. Considering the differences in contrast, patient dose, and artifacts between screen and nonscreen techniques, are there any instances where you would use cardboard exposure holders in spite of the increased exposure? Why?

5

RADIOGRAPHIC FILM: CONTRAST AND PROCESSING

The most common radiographic imaging system in use today is the radiographic film and intensifying screen combination. The role of intensifying screens was discussed in Chapter 4; this chapter will discuss the factors involved in the design, use. and processing of radiographic film. These factors significantly affect the overall contrast of the resultant image and therefore the detail visibility of that image.

THE COMPOSITION OF RADIOGRAPHIC FILM

Radiographic film is composed of two thin (less than 0.0005 inches thick) photographic emulsions coated on a flexible film base (approx. 0.008 inches thick) and covered by a thin protective coating (Fig. 5-1). The film base is made of a plastic material (polyester or cellulose acetate); its primary function is to support the emulsions. A blue tint was first added to the base in 1933 because it was thought to enhance contrast and reduce eyestrain and has been employed ever since.

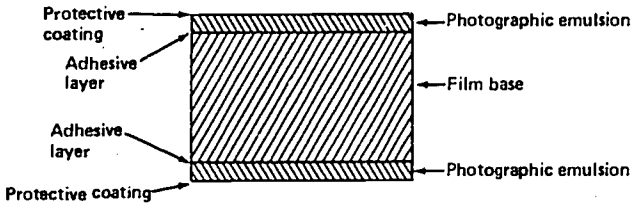


Figure 5-1. Cross-section of an x-ray film.

The emulsions are composed of crystals of photographically active chemical (silver halide) suspended in photographic gelantin. The silver halide is basically silver bromide with the addition of about 1 to 10% silver iodide. This combination results in far more sensitivity than either silver bromide or silver iodide alone. Light photons from the intensifying screens (and x-ray photons) interact with these cyrstals and produce a latent image (explained below). Although the latent image cannot be detected at this stage, it can be converted to a visible image in the development process.

The photographic gelatin serves two important purposes. First, it must allow the silver halide crystals to be coated uniformly and without any clumping across the film base, so that uniform film response across the film (and also between successive films) can occur. Secondly, but more importantly, it must allow the processing chemicals to penetrate to the crystals for the development of the image, without decreasing the strength or permanence of the image. The crystals must be allowed to retain their positional integrity, that is, all of the remaining silver grains must retain their position relative to the others or the image will be destroyed.

FORMATION OF THE FILM IMAGE

The image on a developed radiograph is composed of aggregations of metallic silver atoms that are nonuniformly distributed in the emulsion to form a visible pattern. The basic steps involved in progressing to this condition from the original uniform distribution of silver halide consist of the formation of a latent image and the development and fixation of that image (film processing).

The Latent Image

When radiographic film is exposed to x rays, light photons from the intensifying screens or x-ray photons themselves interact with the crystals of silver halide, thereby releasing electrons from some of the negatively charged bromide ions (Br^-) and causing the evolution of bromine gas (Br_2). The released electrons combine with some of the positively charged silver ions (Ag^+) in the crystal lattice changing them to neutral silver atoms. The aggregation of a small number of silver atoms (generally thought to be fewer than 10) will make the entire silver bromide crystal sensitive to later development. Although this small change cannot be detected, it contains the basis of the completed film image and is therefore called the *latent image.*

Film Processing: Development and Fixation of the Image

The *development* of the image involves the chemical reduction (gain of electrons) of all of the silver ions in the exposed crystals to metallic silver ($Ag^+ + e^- \rightarrow Ag\downarrow$). This chemical reduction actually occurs in all of the crystals, but the silver atoms of the latent image act as a

catalyst to the reaction, allowing the exposed crystals to convert at a much greater rate than the unexposed ones. Like any chemical reaction, the extent of development depends upon the temperature, the concentration of the chemicals, and the total development time. When these factors are appropriately chosen in order to maximize the conversion of the exposed crystals and minimize the conversion of the unexposed ones, the contrast between exposed and unexposed regions will be maximized. Either more or less development will result in reduced contrast. When the developing conditions are such that the contrast is maximized, the processor is said to be *optimized*.

Once the development has been completed, the remaining silver halide crystals must be removed; otherwise they will be slowly reduced with age, darkening the film. The undeveloped crystals are removed in a process called *fixation*. Like the development process, fixation occurs on all of the silver and will remove some of the developed silver as well as the undeveloped silver, but at a far slower rate. Therefore time limits must be placed on the fixation process, although they are not nearly as critical as the limits on the developing process.

The final two steps in the processing of film are washing and drying. All traces of the processing chemicals must be removed since they will cause the film to change in color with age, degrading the quality of the radiograph. The basic steps involved in the processing of an x-ray film are summmarized diagrammatically in Figure 5-2.

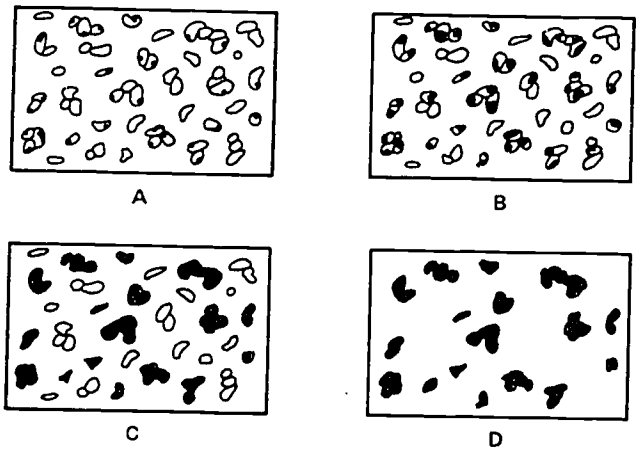


Figure 5-2. Diagrammatic representation of processing action in an x-ray film emulsion(1) A. Distribution of silver halide grains; the dark areas indicate the latent image produced by x-ray exposure. B, Partial development begins the conversion of silver ions to metallic silver in exposed grains. C. Development completed. D. Unexposed silver grains have been removed by fixing.

The advent of *automatic processing* and particularly rapid processing (90 seconds) has forced many changes in film design. Thinner emulsions were required because the processing chemicals must penetrate the emulsion and react rapidly. Also the normal swelling of thick emulsions created transport problems and film jams. However, besides eliminating the time and trouble of hand processing, automatic processing has led to more consistency in film quality by eliminating the "sight development" of films. Sight development involves the deliberate overexposure of the film with subsequent underdevelopment (which saves a few minutes of development time) to produce the desired darkness. In addition to causing inconsistent film quality, sight development requires *significantly* higher patient exposures. (NOTE: This is not to imply that automatic processing has eliminated film processing problems. This is far from true. The next chapter is entirely devoted to methods for trying to achieve optimal, consistent, automatic film processing. It has been estimated that significantly more than half of all radiology film processors are not running optimally.)

Replenishment of Processing Solutions

Both the development and fixation processes are chemical reactions that deplete the original solutions. To maintain the activity of these solutions, and therefore to prevent visible changes in the films, the solutions must be periodically replenished. The exact amount of replenishment required depends primarily on the number of films processed, the size breakdown of those films, and the developer temperature (since the chemicals deteriorate with time, especially at high temperatures). Automatic processors have a metering system which pumps replenisher into the developer and fixer tanks whenever a film is entering the processor. Hand processing tanks are usually replenished with a single addition of replenisher once a day.

Silver Reclamation

An economically and ecologically important consideration in the operation of a radiology department is the reclamation of silver. There are two sources of salvageable silver in the overall process: the discarded fixer and discarded film. The unexposed silver halide that is removed from the film in the fixation process enters into solution and is slowly discarded from the processor as the fixer is replenished. The silver from this solution can be reclaimed by either an electrolytic or an ion-exchange system that can be easily attached to the processor. The silver remaining in the emulsions of discarded x-ray film, the second source of silver, can be commercially extracted from the film. Silver recovery companies will purchase used film for about 2-5% of the original cost of new film.

FILM ARTIFACTS

Artifacts are any abnormalities that appear on the finished radiograph as a result of the improper storage, handling, or processing of the film. Besides detracting from the overall appearance of the film, artifacts may obscure or interfere with the diagnostic information. Exposed film is significantly more sensitive than unexposed film, so extra care should be taken after exposure, and all exposed films should be processed as soon as possible. Although there are numerous reasons for artifacts, many causing distinctive patterns, only general categories will be mentioned here.

Fogging is an overall grayness added to the film as a result of abnormal exposure to some type of radiation. The most common cause of "fogging" is accidental exposure to light. Frequently overlooked as the source of light fogging is improper safelight conditions (a safelight is the low-level light provided in the darkroom to facilitate handling of the film). The response of radiographic film to the light of the appropriate radiographic safelight is very low; however, with enough exposure it will "fog." This overexposure condition can be caused by an overly bright light source, a short safelight to working area distance, an unusually long exposure to the safelight, or an incorrect safelight filter. Other causes of film fog are exposure to ionizing radiation in the film area, storage of film at a high temperature, or the use of film beyond its expiration date.

Radiographic film is sensitive to ***physical pressure.*** Therefore unexposed film should not be stored horizontally with multiple boxes on top because of the pressure on the lower films. However, the most commonly seen pressure artifacts are caused by bending or pinching of the film during handling, which results in dark, crescent-shaped marks on the finished film.

Other artifacts are caused by the discharge of ***static electricity,*** which results in black, lightning-shaped marks and various other characteristic forms. Static electricity artifacts can be minimized by avoiding the sliding of films across other films or across intensifying screens. Traces of ***foreign chemicals,*** especially processing chemicals on the film before processing will also produce artifacts. This type of artifact is most commonly seen as images of fingerprints. There are also ***intensifying screen artifacts*** (poor film-screen contact and dirty screens) which were discussed in the previous chapter.

Improper processing and ***malfunctioning automatic processors*** produce a wide varity of artifacts, from streaks and a mottled appearance to "chewed up" films. These types of artifacts are caused by various difficulties, including processing solutions that are not well mixed, contaminated solutions, and dirty rollers in an automatic processor. Like any other artifact, processing artifacts may interfere with interpretation and may necessitate a second exposure of the patient. Regular preventative maintenance keeps such problems to a minimum, and the overall uniform quality of automatically processed films far outweighs the difficulties.

FILM DENSITY

The image on radiographic film consists of variations in the amount of metallic silver retained in any localized region of the film. When viewed on a viewbox, the amount of silver in a specific area and the intensity of the viewbox light will determine the darkness of the film. In order to quantitate this concept and also to remove the factor of light intensity, the optical density (photographic density, film density, or density) is used. ***Optical density*** (O.D.) is a measure of the proportion of incident light that passes through the film; it is defined by the following equation:

$$O.D. = \log_{10} \frac{I_o}{I_t}$$

where

I_o = the light intensity incident on the film
I_t = the light intensity transmitted through the film

The optical density is a logarithmically linear function of the amount of light transmitted through the film, as shown in Table 5-1. Note that a given numerical change in optical density will always correspond to a given percentage change in transmittance. For example, an increase of 1.0 density units corresponds to a reduction in transmittance to 1/10 of its previous value. An increase of 0.3 density units corresponds to a decrease of transmittance to 1/2 of its previous value.

Table 5-1. OPTICAL DENSITY (O.D.) PERCENT TRANSMITTANCE

% Trans.	O.D.
100	0.0
50	0.3
25	0.6
10	1.0
1	2.0
0.1	3.0
0.01	4.0

The human eye tends to respond in this manner, that is, to percentage changes in transmittance rather than to absolute changes in transmittance. Density differences as small as 0.02 can be visualized over the normal range of densities used in radiology, i.e., from 0.25 to greater than 2.0.

Characteristic Curves

The usual method of representing the response of a film to radiation is by use of the characteristic curve (or

H and D curve, after Hurter and Driffield who first described it, or D log E curve, for density vs. log relative exposure). This curve expresses the relationship between radiation exposure to the film and the resulting film density. It is obtained by exposing film to known amounts of radiation and plotting the resultant density (on the vertical axis) versus the logarithm of the exposure(2). The exposure can either be measured in specific units, ergs/cm^2 or mR, or in relative units (i.e., one exposure is twice the previous one). Characteristic curves are almost always plotted in terms of relative exposure because of the difficulty of making absolute exposure measurements. A typical characteristic curve is shown in Figure 5-3. The curve is approximately *linear* between densities of 0.4 and 2.0 but has a sharp *shoulder* at high densities(3). Also, the curve does not extend to zero density but begins at a density of about 0.2. This flat part

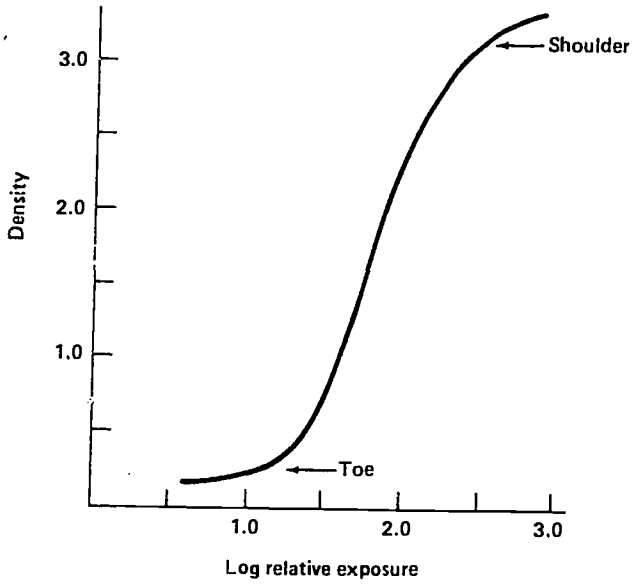


Figure 5-3. Characteristic curve of a typical x-ray film.

of the curve is usually referred to as the *toe*. The lowermost value is the base density plus the "fog" density: the blue-tinted film base has a density of 0.10-0.15 depending on the manufacturer; the fog density (caused by the development of unexposed silver halide crystals) comprises the remainder. This normal background density (about 0.2) of an unexposed film decreases the transmitted light by 37%, yet appears to be almost transparent.

Parameters of the Characteristic Curve

The characteristic curve is the best overall description of film response, but it is cumbersome to use in many instances. There are specific film parameters that can be obtained from the characteristic curve to more readily allow comparison of certain film qualities. As will be seen, these parameters—gradient, average gradient, gamma, latitude, and speed—are closely interrelated.

Gradient

Film *gradient* is simply a measure of the slope (change in film density divided by change in log exposure) of the characteristic curve at any point along the curve. The gradient is an important factor because it defines the difference in density that will result from a given difference in exposure. For example, consider two different thicknesses of some given material such that, when exposed to x rays, the thinner portion transmits 1.6 times as much radiation as the thicker portion. This relative exposure difference translates into a log relative exposure difference of 0.2 (log 1.6 = 0.2). As shown in Figure 5-4, if this object is radiographed at different exposure levels (on different regions of the characteristic curve), the density differences will not be equal. In the "toe" region the density difference is 0.064, and in the "linear" and "shoulder" regions the density differences are 0.75 and 0.12 respectively. With these values, the gradient (change in density divided by change in log relative exposure) can be calculated to be 0.32, 3.75, and 0.60.

In this context the distinction between subject contrast, film contrast, and radiographic contrast becomes quite evident. *Radiographic contrast* is the difference in optical densities between different portions of the radiograph. *Subject contrast* is the ratio of x-ray intensities

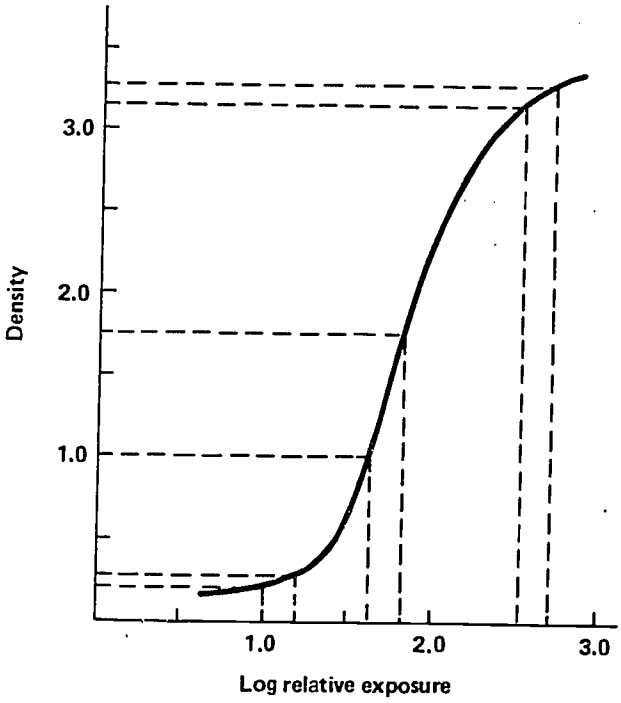


Figure 5-4. Density variations as a function of exposure level. For a given difference in exposure, the difference in density will vary depending upon the position on the characteristic curve.

that are transmitted through the corresponding portions of the subject. *Film contrast* refers to the gradient of the characteristic curve of the film and determines the ultimate radiographic contrast that will be achieved with a given subject contrast. As illustrated in Figure 5-4, "good" subject contrast can yield "poor" radiographic contrast if the exposure levels are inappropriate.

In general, the magnitude of the gradient of the characteristic curve determines whether the subject contrast will be enhanced or diminished in the process of conversion to a visible image. If the gradient is greater than 1.0, the density ratios will be exaggerated over the x-ray intensity ratios, and if the gradient is less than 1.0 they will be diminished. In the example depicted in Figure 5-4, the subject contrast ratio of 1.6 will result in light transmission ratios (radiographic contrast) of 1.2, 5.6, and 1.3 (the antilogarithms of the density differences) at the toe, linear region, and shoulder of the curve respectively(4).

Gamma and Average Gradient

Since it is not always convenient to refer to the characteristic curve when comparing films, a single number has been sought. The *gamma* of a film is defined as the gradient of the linear portion of the curve. Unfortunately some films have very short linear regions and the exact boundaries of the linear region are difficult to determine since these regions are not truly linear. A more valuable number is the average gradient of the curve. The *average gradient* is defined as the slope of the straight line between the two endpoints of the useful range of densities. For radiographic film this range is arbitrarily defined as 0.25 to 2.0 above base density and fog, i.e., a *net* density of 0.25 to 2.0, which usually corresponds to an *actual* density of about 0.45 to 2.2 (see Fig. 5-5).

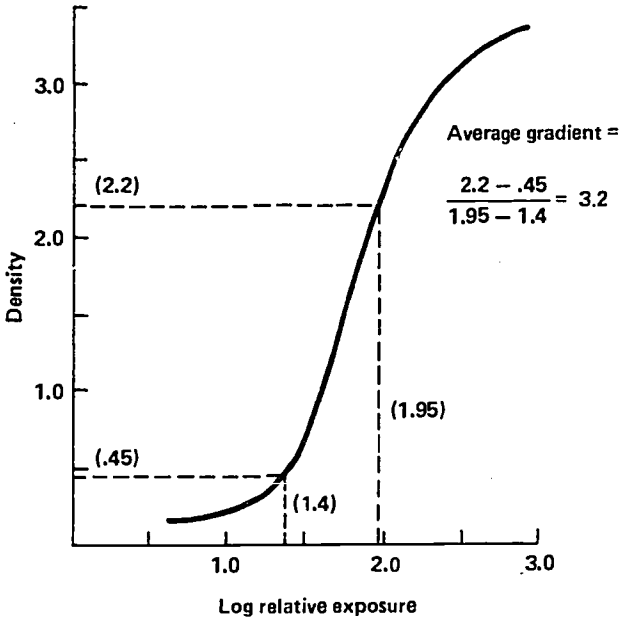


Figure 5-5. Calculation of the average gradient of an x-ray film.

The labeling of a particular film as "high" or "low" contrast is based partially on the value of the average gradient plus the subjective opinions of those people using the film. In general, all medical x-ray films have average gradients in the range of 1.75 to 3.5. Therefore, even "low" contrast films will enhance the subject contrast in producing the visible image (except for very low densities on the "toe" region of the characteristic curve).

Latitude

The range of exposure levels that can be imaged on the film is called the film *latitude*. The useful density range defined previously (0.45 to 2.2) is generally used as the basis for determining latitude. As one would expect, latitude and contrast are inversely related; one increases as the other decreases (see Fig. 5-6). A high contrast, low latitude film requires more accurate techniques factors (the margin for error is less) but will provide the greatest contrast between similar structures.

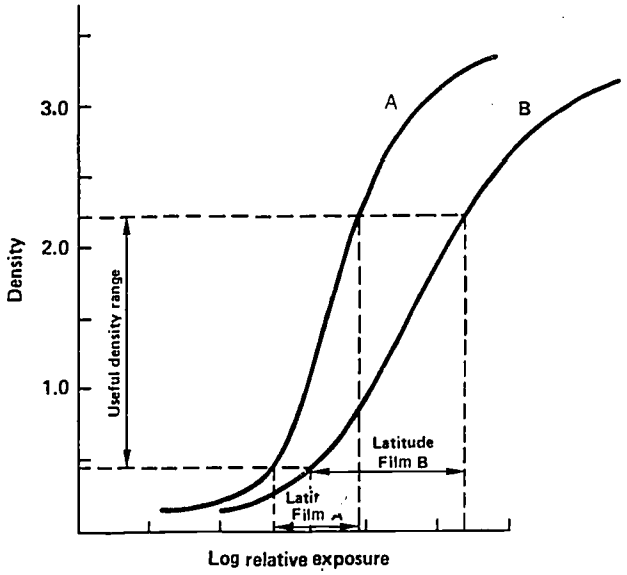


Figure 5-6. Definition of film latitude:
Film A is a high contrast, low latitude film
Film B is a low contrast, high latitude film.

Speed

The film parameters discussed thus far have been related to the shape of the characteristic curve, primarily the slope. Another important parameter is film *speed*, the exposure necessary to produce a given optical density. This parameter determines the location of the curve along the exposure axis, as illustrated in Figure 5-7. Film speed is inversely proportional to the exposure required to produce a given density, i.e., a high speed film requires a low exposure. Absolute values of x-ray exposure for

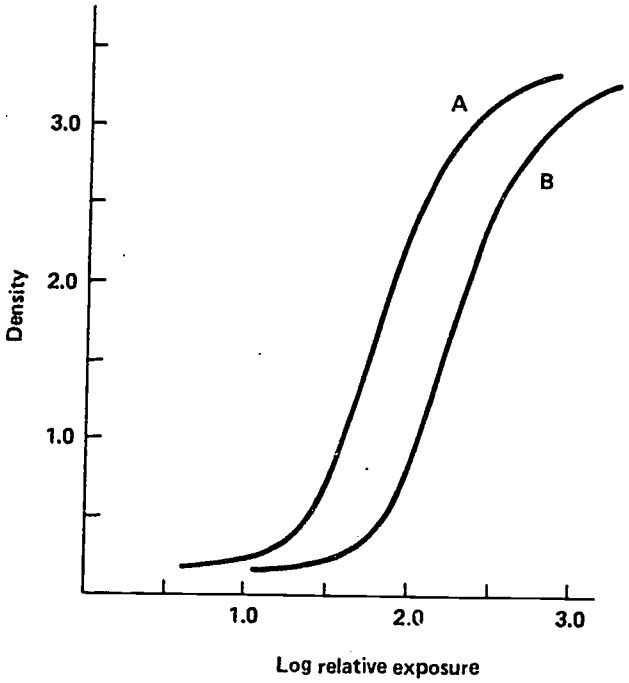


Figure 5-7. Two films of different speed: Film A is a faster film (requires less exposure than Film B).

direct exposure film and of total light energy for intensifying screen film can be obtained and film speeds determined from those values, but usually only relative film speeds are determined. If the characteristic curves of a group of films are given, the curve of the fastest film will be to the left, and that of the slowest to the right. One film of the group will be arbitrarily assigned a value, such as 100, and the speeds of the other films will then be related to that value. For medical films, the speed is usually determined at a net density of 1.0 (actual density about 1.2) because this is near the center of the useful range of densities. However, this is an arbitrary choice and the speed could be determined at any density desired. The relative speed of a high contrast film as compared to a low contrast film can be a problem since the characteristic curves could intersect, as illustrated in Figure 5-8. At low densities the low contrast film would be faster while at high densities the high contrast film would be faster.

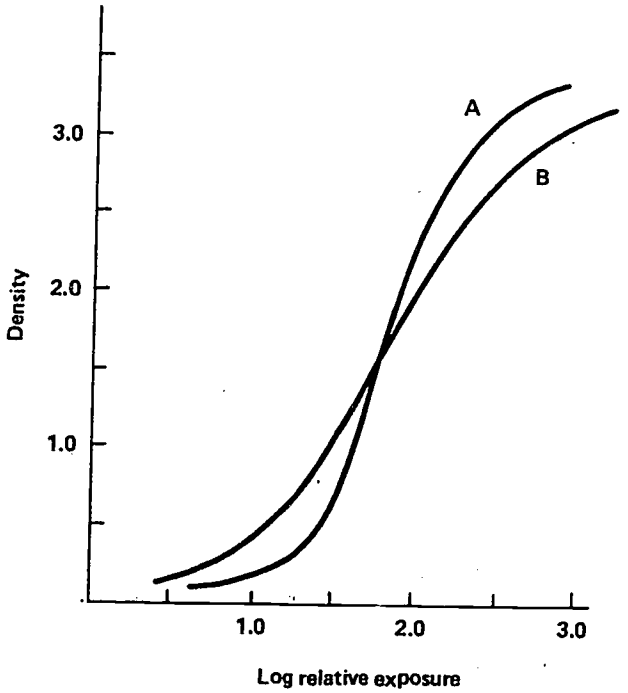


Figure 5-8. Two films of different speed and contrast: Film A is a higher contrast film than Film B. Their relative speeds depend upon the density at which the speed is determined.

FILM FACTORS AFFECTING RADIOGRAPHIC CONTRAST

It is obvious that for "good" detail visibility there must be "good" radiographic contrast. However, radiographic contrast is limited by the film contrast, which depends not only on the inherent characteristics of the film but also on various exposure and processing factors.

Level of Exposure

For maximum contrast the film should be properly exposed, or more importantly, the specific area of interest should be exposed to a density in the range of 1.0-1.5. Referring back to Figure 5-4, if the object of interest is exposed in the "toe" or "shoulder" regions, the radiographic contrast between two similar areas will be low and a distinction might not be possible. However, if the exposure is in the linear region, the contrast will be maximized. In Figure 5-4 the linear region extends from about 0.7 to 2.5; the contrast will be approximately constant in this region. Although the characteristic curve is not linear between 0.3 and 0.7 this region is very useful because the eye is highly sensitive to small density variations in this range. Densities greater than 2.0 are considered undesirable in clinical practice because under normal viewing conditions the eye cannot differentiate well at these high densities. However, the characteristic curve of almost all radiographic films is linear to 2.5 and many to even 3.0. Thus, beyond a density of 2.0, the information is probably available and can be brought out with a "bright light." These films can be read without the need for reexposing the patient, but films that are "too light" do not have sufficient radiographic contrast to ensure detail visibility and will have to be retaken.

Processing

The photographic processing of the film is critical to the production of good quality radiographs. In the ideal processing situation all of the exposed silver halide crystals and none of the unexposed crystals would be converted to metallic silver. Unfortunately the conversion of both unexposed and exposed crystals will occur

simultaneously but at much different rates. The problem is determining the point at which development should be stopped. Assuming that fresh processing chemicals are used, the time and temperature of development are the only variables that must be determined. Increasing either of these factors will increase the speed of the film (i.e., the characteristic curve will shift to the left). Increasing either factor will also increase the average gradient up to the maximum beyond which it will slowly decrease. This is illustrated in Figure 5-9. However, as time or temperature are increased, fog will also increase due to the development of unexposed crystals. It is actually the development of these unexposed crystals which results in the decrease in the average gradient.

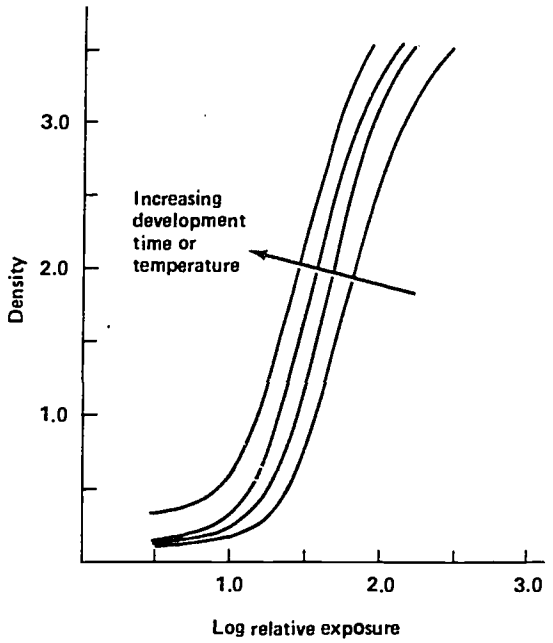


Figure 5-9. Family of characteristic curves obtained by varying development time or developer temperature (while holding the other constant).

Using the family of curves in Figure 5-9, the average gradient, film speed, and fog level can be measured as a function of either development time or temperature. This information is plotted in Figure 5-10. Specific graphs like these for both development time and temperature are used to determine the optimum processing conditions for a particular type of film with particular processing chemicals. The importance of processor optimization and the establishment of a processor quality assurance program will be discussed in detail in Chapter 6.

Screen vs. Nonscreen Exposures

In the previous chapter a screen exposure was shown to have a greater contrast and much higher speed than a direct exposure of the same film. The difference in speed depends upon the speed of the screen, the kVp used, and

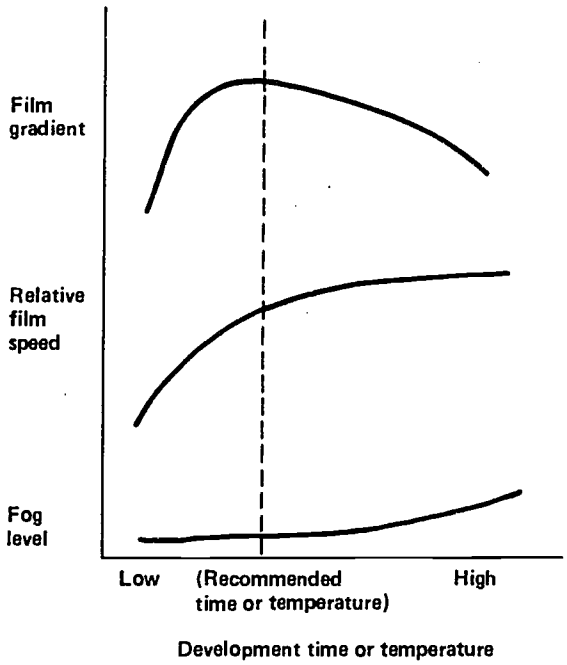


Figure 5-10. Average gradient, film speed, and fog level curves (obtained from the family of characteristic curves depicted in Fig. 5-9).

the particular subject. Figure 5-11 illustrates the characteristic curves of a screen film used with and without intensifying screens. The shape of the curves confirms the lower contrast of direct exposure radiographs. The reason for the difference is based on the differences in film response to light exposure as compared to x-ray exposure.

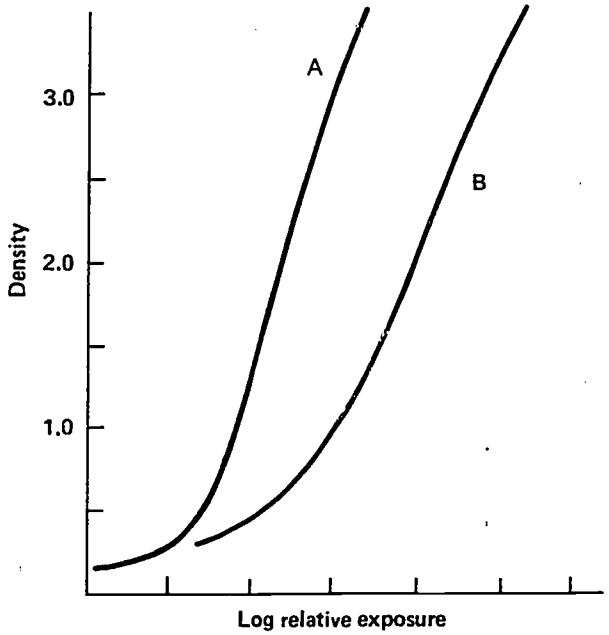


Figure 5-11. Characteristic curves of a screen film exposed with (A) and without (B) intensifying screens.

CHOOSING THE FILM

An intelligent comparison between different types and brands of films is difficult to make. One person might feel that a specific film is slightly faster than another while a second person indicates just the opposite. "Minor" variations in processing temperature or a difference in the brand or age of intensifying screens can easily account for the difference. Various film manufacturers can provide characteristic curves comparing their films, but comparisons between brands are not usually available. The only guidelines available are the advertising claims: "high contrast, fine-grain film," "combines speed with high contrast," "exceptional clarity and resolution, with latitude and low fog level," "medium speed, sharp definition, rich blacks." Clearly the only valid comparison is under actual conditions of use with the cassettes, processors, and personnel that will be involved.

Theoretically the film used in a particular clinical situation could be chosen to coordinate with the available subject contrast. If the subject contrast is low, as with the plain film of the abdomen, a high contrast film would be appropriate, while high subject contrast would indicate the use of a lower contrast film. The need for "good" overall radiographic contrast is obvious. If the contrast is too low, diagnostically significant variations may not be distinguished, while if the contrast is too great, information may be lost in the extreme densities.

In actual clinical practice, a single type of film is usually chosen that best satisfies all of the various film parameters discussed previously, and this film is used in all situations; except for special purposes such as mammography or cineradiography. The subject contrast is then altered by kVp variation to produce films with the desired contrast. This approach avoids the logistical problems of having many different films, allows the processor(s) to be optimized for that one type of film, and also eliminates the possibility of using the incorrect film.

SUMMARY

X-ray film consists of photographic emulsions coated on both sides of a blue-tinted film base. Most x-ray emulsions are specifically designed to be sensitive to the blue light emitted by most intensifying screens. Light and x-ray photons create a latent image in the emulsion which, in the development process, results in the production of a corresponding pattern of metallic silver. The quantity of silver at any point in the radiograph affects the amount of light that can be transmitted through the film; a measure of this light transmission is the optical or photographic density. The diagnostically useful range of densities is from 0.25 to greater than 2.0. The response of a particular film to radiation exposure is graphically depicted by the characteristic curve; analysis of this curve provides information about the contrast, relative speed, and exposure latitude of the film. The precise shape of the characteristic curve is not constant, but varies with film processing conditions and whether the film was exposed with or without intensifying screens. Assuming proper film exposures and optimum processing conditions, the film chosen under actual conditions of use in radiological practice will depend subjectively on the degree of contrast and the level of detail visibility acceptable to the radiologist(s).

REFERENCES AND NOTES

1. Adapted from *The Fundamentals of Radiography*, Eleventh edition, Eastman Kodak Company, Rochester, New York, 1968, p. 51.
2. The logarithm of the exposure is plotted because two exposures whose ratio is constant will always be separated by the same distance on a logarithmic scale no matter what their absolute values.
3. Density and the logarithm of exposure are linear, not density and exposure.
4. The optical density is the logarithm of the ratio of light transmissions. Therefore the ratio of light transmissions is the antilogarithm of the optical density.

LABORATORY EXERCISE 5

RADIOGRAPHIC FILM: CONTRAST AND PROCESSING

The most common imaging system used in radiology is radiographic film, usually in conjunction with intensifying screens. The ultimate detection of details in a radiograph is therefore quite dependent upon the specific type of radiographic film used and the various factors involved in the handling, exposure, and processing of that film. This exercise investigates these factors and how they may affect the contrast and sharpness of the completed radiograph.

Equipment

This exercise is to be conducted in the Radiological Health Sciences Learning Laboratory and will require the use of the following apparatus:

Small teaching x-ray machine
Assortment of aluminum filters
Assortment of lead diaphragms
Cassettes with par speed screens
Radiographic film
Radiographic knee phantom

Procedure

1. Safelight fogging

To properly test the "safety" of darkroom lighting conditions, a radiographically ***exposed*** radiograph should be exposed to the safelight. (A slightly exposed film is more sensitive to additional exposure than an unexposed film, as can be seen by examining the shape of the characteristic curve.)

Exposure parameters:
kVp — 80
mAs — 9
Diaphragm — none
Filtration — 2.5 mm Al added
Distance — shelf 5
Cassette — 8 × 10 inch, par speed screens

Make two separate identical exposures of the aluminum stepwedge. Note the location of the stepwedge on each film so that you can expose half of the image (lengthwise) to the safelight while keeping the other half covered. On one film expose half of the stepwedge image to 2 minutes of safelight, on the other expose half of the image to 4 minutes of safelight. Process the films and check for evidence of fogging. (If densitometer evaluation is used, there should be no more than a 0.05 increase in density on any step.)

2. Film Artifacts

Create some of the following artifacts on a film to gain an appreciation of the sensitivity of the film and the cause of some of the common artifacts. Be moderate in creating these artifacts. You are only interested in seeing the effects of mishandling that could reasonably be expected to occur. ***Do not fold*** the film as it will cause the processor to jam.

a. Crescent-shaped marks — caused by bending the film, usually when picking up a sheet.

b. Static electricity — usually caused by sliding one film across another or across an intensifying screen when loading or unloading the cassette. Static electricity is very dependent upon particular climatic conditions, but for purposes of an example, static effects can usually be created by combing one's hair and touching the comb to the film.

c. Fingerprints and smudge marks — caused by handling a film with moist fingers, particularly when traces of fixer are on the fingers.

d. Scratch marks — caused by fingernails, rings, sharp edges on cassettes or tabletops, or by automatic or manual processing racks.

e. Pressure effects — caused by excessive pressure on the emulsion, often as a result of storing a heavy object on top of the film in its box or by dropping an object on the film.

f. Light-struck film — often caused by faulty cassette catches or by the accidental opening of the film bin in the light.

Process the film in the automatic processor and observe the visual effects. The greatest difficulty with artifacts is the question of the necessity of a retake, weighing the additional patient exposure against the possible loss of significant diagnostic information.

3. Overall Density Level

Exposure parameters:
kVp — 60
Diaphragm — 3 inch diameter
Filtration — 2.5 mm Al added
Distance — shelf 5
Cassette — 8 × 10 inch, par speed screens

Make a properly exposed (16 mAs) lateral radiograph of the knee phantom, as well as an overexposed one (80 mAs) and an underexposed one (6 mAs). Although these are extreme cases, the overexposed film can be read using a "bright light"; all of the information present in the properly exposed film can probably be visualized. On the other hand, the underexposed film does not have the necessary information and must be retaken.

4. Different Radiographic Films

Using the technique for the properly exposed film in part 3, make additional exposures of the knee phantom using different films from different manufacturers. If green-sensitive film and rare-earth screens are available, include this also in your selection. Process the films in the automatic processor and observe differences in speed (reflected by the overall density) and contrast.

5. Radiographic Mottle

Make the following exposure with no object in the beam, to illustrate radiographic mottle.

Exposure parameters:
kVp — 60
mAs — 1
Diaphragm — none
Filtration — 2.5 mm. Al added
Distance — shelf 5
Cassette — 8 × 10 inch, par speed screens

Process the film and examine the mottle.

QUESTIONS

1. What specific radiographic situations can you think of where radiographic mottle might interfere with the visualization of details?

6

QUALITY ASSURANCE OF AUTOMATIC FILM PROCESSING

The previous exercise dealt with the film portion of the radiographic film-screen imaging system. Variations in image quality, as measured in terms of contrast, resolution, and overall film density, can be obtained by appropriate choices of kVp, mAs, focal spot size, film, and intensifying screens. These variations are predictable and are exploited to produce the best image based on the subject contrast inherent in a specific type of examination.

Variations in processing conditions can also have a dramatic effect on image quality. However, processing is not generally utilized as a method to modify image quality; on the contrary, processing should be controlled to remain a *constant* so that it will have no variation in effect on different radiographs.

Processing chemistries and suggested processing conditions (developer temperature, time in developer, replenishment rates, water temperature) are designed to give optimal results with specific radiographic film. Deviation from these conditions will mean a degradation of the resultant processed images. The magnitude of this degradation may be significant; processing in substantially underreplenished chemistry could require an increase of 2-3 *times* the normal exposure to obtain comparable photographic image density. Other factors such as developer temperature or development time can have similarly dramatic effects.

In most radiology departments the automatic processor is considered to be truly "automatic" and is overlooked as a source of improperly exposed films; the radiographic units are usually blamed. Various studies of "retakes" in diagnostic radiology departments have shown that the most common cause (35-50%) of retakes is a too light or too dark film(1,2). Although such films are most commonly caused by machine malfunction, improper speed intensifying screens, or an incorrectly measured patient thickness, improper processing may account for a significant percentage of them(3). Unfortunately, processing is usually considered only after it is noticed that every film is too light (or too dark).

Therefore, to avoid the difficulty of dealing with a serious processing problem after-the-fact, as well as to avoid the unnecessary patient exposure involved in processor-caused retakes, it is imperative that a department implement a quality assurance program for automatic film processors.

PROTOCOL FOR A PROCESSOR QUALITY ASSURANCE PROGRAM

The basic procedure involved in conducting a processor quality assurance program is simple. It consists of the following steps:

1. Exposure of a strip of film to a precisely controlled light source through a series of optical filters; this will yield a set of light-exposed "steps."
2. Processing of the exposed strip of film in the processor that is to be evaluated; the light-exposed steps produce a set of optical density steps.
3. Measurement and recording of the optical densities of the processed "steps."
4. Measurement and recording of data pertinent to the operation of the processor and chemistry.
5. Evaluation of the data.
6. Corrective action (if the above data falls outside of the established limits of acceptability).

The following sections will elaborate on each of the above steps and on the equipment necessary to perform them.

Exposure of the Film Strip

The Sensitometer

The exposure of the strip of film is best accomplished with a ***sensitometer,*** a device that produces a controlled, accurately repeatable amount of light (Fig. 6-1). The light source may be an incandescent bulb or electroluminescent panels. The amount of light emitted may be controlled by a timer, a light shutter, or a capacitor discharge system. The emitted light then passes through a "sensitometric step tablet" which consists of a series of optical filters, normally 11 or 21; these filters transmit uniformly increasing incremental quantities of light to the film strip. For sensitometric evaluations the density range of the step tablet should be at least 3.0 and each step

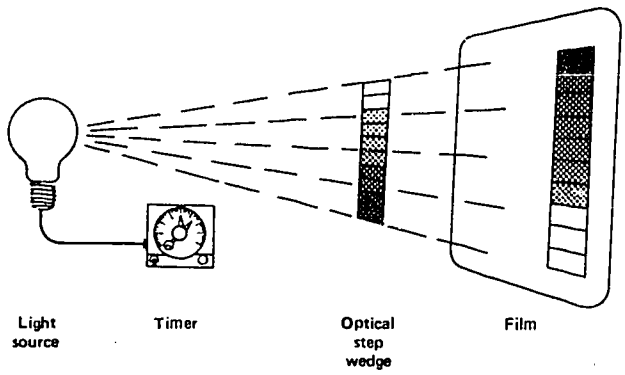


Figure 6-1. Diagrammatic representation illustrating the principle of operation of a sensitometer.

should be wide enough so they can be read by a densitometer without influences by edge distribution(4,5). The exposed film strips will therefore contain the latent image of a series of incremental densities; once these film strips are processed they are called ***sensitometric control strips***.

Many sensitometers are available, ranging in price from $200 to $1500. They will all do an adequate job for day to day quality assurance evaluation. However, a specific department will have to evaluate which extra-cost features are needed for any other uses they require(6,7).

Film Emulsion Considerations

Radiographic as well as photographic film is coated with an emulsion that is sensitive to both light and x radiation. Manufacturers mix the emulsion in large batches and coat hundreds of thousands of square feet of film at one time. Although their quality control procedures are very stringent, there will be slight variations between emulsion batches. These variations can often be seen with a sensitometric quality control program. Therefore, to avoid confusion of processor variability and emulsion variability, a 3- to 6-month supply of sensitometric control film ***from one emulsion batch*** should be obtained. If stored properly (50-70°F, away from any sources of radiation) there should be no degradation over that time period. The film should be packaged in small quantities (50-100 sheets) so that only a portion of the entire supply needs to be open at one time.

It is important that the emulsion used for the sensitometric control strips match the emulsion normally used in the department (or in that specific processor), both in brand and type. (One should also be aware that the use of film from one manufacturer and chemistry from another presents a potential source of problems. Manufacturers invest large amounts of effort and money in designing their films and chemistries so that they work optimally together, and in maintaining that compatibility as products are improved. Although most x-ray products from one manufacturer are compatible with the appropriate products from other manufacturers, there is no guarantee of future compatibility as product modifications occur.)

Preexposed Sensitometric Control Strips

An alternate method of processor control utilizes preexposed sensitometric control strips. Preexposed strips are exposed well in advance of use and supplied through commercial channels. They have the advantage of being exposed under much more precise conditions than are available in an average x-ray facility and can be used to quickly and easily determine if a processor is operating in accordance with the manufacturer's recommendations.

However, there are different opinions about the value of preexposed strips. Film response, expressed in terms of optical densities resulting from a given exposure to the film, varies as a function of elapsed time between exposure and development. As a result, preexposed strips are not as sensitive to slight processing variations (i.e., temperature variations, chemical concentrations) as are freshly exposed strips. Whether this decrease in sensitivity decreases their value in a quality control program is a matter of controversy(8,9,10); however, preexposed strips have been routinely utilized in the graphics art industry for many years. NOTE: The manufacturers of preexposed strips recommend keeping the strips frozen until needed.

Processing of the Film Strip

The one guideline that should be followed in exposing and processing control strips is ***consistency***. The sensitometric strips should be handled in exactly the same way each day so that variations in results will be indicative of problems in processing, not in performance of the test. For sensitometer-exposed strips the interval between exposure and processing should be consistent.

Because of variation in sensitivity as a function of time between exposure and processing, it has been recommended that the time delay should be between 30 minutes and 4 hours(4,9). A slight increase in film density occurs in the first minutes after exposure, and a slow decline in density will occur after 2 to 4 hours. Practically speaking, however, the most consistent results will be obtained by processing the strips immediately after exposure, thereby eliminating the need to measure the time elapsed after exposure and avoiding the possibility of significant variability in this time interval.

Likewise, the time of day that the strip is processed should be consistent. The easiest time would be first thing in the morning after the machine has been warmed up, but before any films have been processed. Strips run at other times are likely to show greater fluctuation, since there would have been a large number of films run or no

films run immediately prior to processing the sensitometric strip and the solutions may or may not be at chemical equilibrium. For this very reason it is also important to process additional strips at several other times during the day to detect any significant changes that may have occurred in processing conditions.

A control strip will produce different densities depending upon which end was fed into the processor first. To avoid variability, it is advisable to process all strips with the end with the lightest densities (least exposure) first. Preexposed control strips are notched on one end to facilitate their proper orientation when processing. However, with sensitometer-produced strips, it may be difficult to remember which end received the least exposure and should be processed first, especially if there are several operators. In addition, the least dense area is not always at the end (depending on the type of sensitometer used to produce the strip), so that it may not be possible to follow this recommendation. Therefore, it would be best to process sensitometer-produced strips in an orientation parallel to the rollers in the processor.

Similarly, it is advisable to enter the strips into the processor in the same part of the feedtray (right, left, center). Although this is a minor consideration, it would eliminate any variability that could be introduced as a result of local inhomogeneities in temperature, agitation, or replenisher concentration throughout the tanks.

Measurement and Recording of Optical Densities

All of the information generated by a sensitometric strip quality assurance program is contained in the level of darkening (optical density) of the strips. Optical density (O.D.) is defined as:

$$\text{O.D.} = \log_{10} \frac{\text{Intensity incident on film}}{\text{Intensity transmitted through film}}$$

Optical density is measured by use of a ***densitometer.*** The densitometer consists basically of a light source and a photocell for measuring the transmitted light. When properly calibrated, these units will typically read optical densities from 0 to 3.0 (or more) with an accuracy of ±0.02 Using the densitometer, the densities of the various "steps" of the senitometric strips are measured and recorded.

Measurement and Recording of Processor Parameters

There are a number of processor operating parameters that should be measured and recorded when a sensitometric strip is processed. These include:

1. Developer temperature
2. Water temperature and flow rate (if possible)
3. Developer and fixer replenishment rates (if readily measurable)
4. Total cycle time or processor speed (if the processor has a variable speed drive).

At the same time that these parameters are measured, check the solution level (it will be low if no replenishment is occurring), and check for agitation (to see if the circulation pumps are operating). CAUTION: A mercury thermometer should ***never*** be used for measuring processor temperatures. Mercury is a strong contaminant of photographic developer in addition to being highly toxic to personnel at extremely low concentrations. Therefore if a thermometer were to be broken, it could contaminate the darkroom, particularly working countertops. Mercury may be absorbed directly through the skin and may also be inadvertently ingested should food be eaten with contaminated hands. Stem-type dial thermometers are rugged and inexpensive, but need to be checked frequently against a standard thermometer. The newer thermistor digital thermometers, although more expensive, are accurate, quick, and simple to use.

As mentioned previously, *consistency* is extremely important. The developer temperature should be measured in the same place each time, preferably in the middle of the tank. There are temperature inhomogeneities within the tank due to the location of the developer heater and the recirculation inlets; and the temperature at the sides of the tank is affected by temperature gradients through the tank walls because of the temperature outside of the tank.

Aside from recording the actual operating parameters, it is necessary to establish and maintain an accurate permanent record of all processor maintenance activities in order to provide a proper quality assurance program. Such data can be used to pinpoint the probable cause of processing problems that will be detected by the program. A chronological (date and time) ***processor maintenance log*** of the following actions should be maintained:

1. Change of developer replenishment rate
2. Change of fixer replenishment rate
3. Addition of developer replenisher to storage tank (premixed or self-mixed)
4. Addition of fixer replenisher to storage tank (premixed or self-mixed)
5. Processing chemicals changed in internal tanks
6. Processor and/or racks cleaned
7. Developer filter changed
8. Water filter changed
9. Any other change, repair, or maintenance, routine or otherwise.

This data can be invaluable in diagnosing the cause of sudden changes in processing activity. For example, if the sensitometric activity of the processor began a steady decline on Thursday morning, and the log showed

that new developer replenisher was added to the storage tank on Wednesday afternoon, that replenisher should be investigated as the most probable cause of the problem.

Evaluation of the Data and Corrective Action: A Sample Processing Control Chart

To properly evaluate the significance of daily sensitometric data, it is necessary to obtain normal baseline data and to establish control limits beyond which action should be implemented. A useful tool for accomplishing this task is a control chart. A *control chart* is a graphical presentation of a sequence of data points; the graph includes an average operating level and both upper and lower control limits. The upper and lower control limits establish the normal operating range for the parameter under measurement. Whenever the measured value lies outside of these limits, corrective action must be taken.

Sensitometric control strips generally have either 11 or 21 different density steps. Although these steps can all be plotted to produce a characteristic curve (see Chap. 5) for that specific film-processor combination, it would be too time consuming and would serve no useful purpose to handle that volume of data on a daily basis. Instead, once the processor is optimized (see below) a characteristic curve is plotted and several appropriate values to be used for the control chart are chosen. Gray recommends using three steps that are closest to 0.25, 1.00, and 2.00 optical density units above base plus fog; an unexposed portion of the film is used for the base plus fog measurement(4,5). Once the specific steps are chosen, they are consistently used in maintaining the control chart.

Figure 6-2 shows a sample control chart. The three specific control graphs are as follows:

1. Density Difference (DD): The difference between the high density step (2.00 above B + F) and the low density step (0.25 above B + F). This corresponds roughly to an average gradient or film *contrast* measurement.
2. Medium Density (MD): The actual density of the mid density step (1.00 above B + F). This corresponds roughly to a film *speed* measurement.
3. Base plus Fog (B + F): The density of an unexposed section of the film.

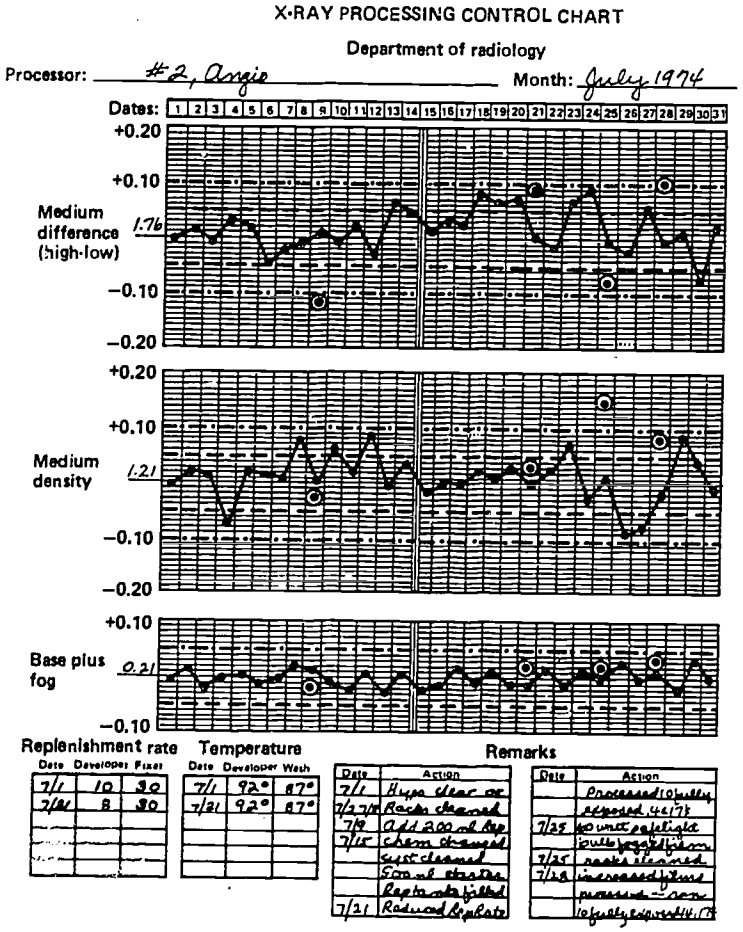


Figure 6-2. An x-ray processing control chart(4).

In this example, the processor was assumed to be optimized on day 1 and the respective densities were entered on the chart. Control limits of ±0.10 density units were drawn in for the density difference and medium density charts. The base plus fog control limits were drawn in at ±0.05 density units.

The following excerpt from Joel Gray(4) describes how this sample control chart would have been used in actual practice. His comments refer to a specific processing system (film, processor, and processing chemistry) which most likely will differ from that in use in your own department. Therefore specific numbers of films, volumes of chemistry, and replenishment rate numbers will probably not correspond to your situation; however the general concepts will be applicable to any situation.

". . . On the 9th of July values of 0.19, 1.18, and 1.64 were measured and plotted. Note that the 1.64 value lies outside of the LCL [lower control limit] for the density difference. Another sensi strip was immediately processed and read with similar results indicating that there probably has been a change in the process. The points associated with the out of control condition are circled as shown in [Figure 6-2]. Since the levels were low, a total of 200 ml of additional replenisher was added directly to the developer tank. With the addition of 200 ml the levels were within the control limits. The new data points from the control strip of 0.22, 1.21, and 1.77 were plotted and used as the point to which the lines are drawn. Also a note was made under 'Remarks' to indicate the modification to the developer.

"The process seemed to be running in good control, but the 6-month period for cleaning (as recommended by the manufacturer) was encountered on the 15th of July. The machine was stripped, cleaned with system cleaner; the appropriate preventive maintenance was carried out; the tanks were seasoned. . . ; and fresh developer was added along the recommended amount of starter. [EDITORIAL NOTE: Many processor experts from both chemical manufacturing and processor service companies recommend specifically against using systems cleaner because of the harsh chemicals involved and because good cleaning can be accomplished without them. Residual traces of these chemicals have been implicated as a major source of sensitometric variability.] The developer replenisher tanks were also cleaned and refilled. The new values from the control strips (0.19, 1.19, and 1.77) indicate that the new chemicals are now in control. The data is plotted and the machine is put back into operation. (Note that a double line emphasizes that a change in chemistry was made.)

"Over the next 6 days, the levels of the MD and DD appear to be rising slightly indicating that a problem has possibly developed. The chart indicates that the replenisher may be slightly more concentrated than normal or that the replenishment rate may be set too high. Since the additional replenisher has driven the process upward it is necessary to correct for this condition and make a correction to the replenishment rate to avoid this problem in the future. The simplest method for correcting for overreplenishment is to process completely exposed radiographic films without replenishment . . . . Ten sheets of completely exposed 14" × 17" x-ray film were processed without replenishment which brought the levels back into control and the replenishment rate was reduced from 10 to 8 while the fixer replenisher rate remained unchanged. All of these actions are recorded on the lower section of the control chart.

> "*The fixer replenisher rate should always be operated at the level recommended by the manufacturer and should not be decreased below the recommended level when the developer replenisher rate is decreased, unless the manufacturer provides other recommendations.*

"The processor appeared to operate normally until July 25th when an increase in the MD occurred along with a decrease in DD. This combination of changes is normally indicative of fogged film. Another sensi strip was run from a previously unopened box of film with all safelights and indicator lights turned off. This strip indicated that there was no fog on the film in the box. Likewise, a strip was exposed from the original box of film, in total darkness, which indicated that the original box of film had received some fog, ***even though there was no apparent fog on the clear areas of the film.*** Another sheet of film was removed from the second box of film, the one which we knew was not fogged, and the box was closed and sealed in total darkness. The safelights were turned on and the sensi strip exposed and processed in the normal manner. The resultant strip gave densities similar to those circled points on the 25th of July. This indicated that there must be light fog from the safelights. Upon checking the safelights we found that 60-watt bulbs were installed by the maintenance crews since they 'rebulbed' the department and did not have any 15-watt bulbs. The 60-watt bulbs were replaced by 15-watt bulbs and the darkroom checked for safelight and light leaks . . . and found to be safe. Another sensi strip was exposed from the second box of film, with the safelights on, and the resultant densities were found to be 0.21, 1.22, and 1.75; again within control limits. The first box of film was discarded since it was exposed to fogging light and replaced with the second box for quality assurance purposes.

"On July 28th an increase in the values beyond the control limits of the MD and DD were noted. Upon checking, it was found that two other processors were shut down and all of the films were run in this processor, plus its normal load of films. This caused overreplenishment of the developer which was corrected by processing 10 sheets of fully exposed 14" × 17" film without replenishment. This time, unlike the last incidence of overreplenishment, no modification was made

in the replenishment rate since the change in the process level was caused by a change in processing load which was back to normal the next day.

"The previous discussion should give you some idea of how the control charts must be maintained and how they can be used to your benefit. Keep the following rules for maintaining control charts in mind:

1. Draw in the control limits in red ink. When a data point reaches or exceeds the control limit, action is required.
2. Fill in all information on the control chart regularly.
3. Connect the data points with straight lines — watch for trends.
4. Plot the data which is out of control and circle all three points even if only one point is out of control. Then plot the data points which correspond to the corrected levels while indicating the changes in the 'Remarks' section.
5. Indicate changes in chemistry by a double line on the control chart.
6. *Keep the control chart up to date,* and examine the control chart daily for trends or indications of problems."

PROCESSOR OPTIMIZATION

The importance of optimum processing conditions to maximize the contrast between exposed and unexposed regions of the film was mentioned in Chapter 5. Most departments will want to follow the recommendations of the film manufacturer as to the chemistry and processing conditions to be used. (Remember, it is important to not mix film and/or chemistries in one processor and inadvisable to mix them within the department.) However, if there is some doubt that the processor is producing optimally-developed films under these conditions, or if a film-developer combination is being used for which manufacturer-recommended processing conditions are not available, then the optimum processing conditions should be experimentally determined. To accomplish this, the developer temperature normally recommended by the manufacturer for the chosen film with a similar developer is selected as a starting point. If the processor is of the variable-speed type, the speed is set to that recommended for a similar film and developer and is held constant. A family of characteristic curves (see again Fig. 5-9) is then obtained beginning at a temperature 5° below the selected midpoint to 5° above this midpoint, in increments of 2° (a total of 6 curves). Using the family of curves thus obtained, the density difference (average gradient), medium density (film speed), and base plus fog (fog level) are then plotted as a function of temperature. The optimum developer temperature must be carefully selected from these three graphs; the film gradient and film speed should be maximized while the fog level is minimized.

All processors in a department should be set to operate at the same level sensitometrically (due to variations in individual processors and their use, this could mean slightly different temperatures, replenishment rates, and transport speeds). This greatly facilitates the processor quality control program, and in addition, any one processor can help take up the load when another is out of operation. If one radiologist or service prefers a different contrast than that being obtained, it should not be accomplished by modifying the established processing conditions; this would result in non-optimum processing, at the expense of both image quality and patient dose. Rather, a desired change in contrast should be achieved by modifying the kVp used to expose the x-ray film.

An essential part of the optimization process is providing the proper utilities. The physical plant is usually asked to provide power, water, drain, and exhaust. The importance of the water supply is often overlooked. The water serves two important functions in an automatic processor: a joint role (shared with the developer heater) in developer temperature regulation, and washing of the film.

Unless one of the "cold water" automatic processors is used, a high-quality thermostatic mixing valve (controls to ±1°F) is essential. Since pressure variations are unavoidable in a hospital, the mixing valve should have the pressure-balancing option. Water filters should be provided in both the hot and cold water supplies to keep any particulate matter from fouling the mixing valve as well as to avoid deposits on the films. A flow meter should be provided so that the water flow can be set to any level desired and also to monitor the condition of the filters (the flow rate will drop as the filters become clogged). Pressure meters can be installed before and after each filter to indicate if they are clogged, but a flow meter should still be used to indicate total water flow to the processor.

Care should be taken in using standby units. These units conserve water and power by cutting down on water flow, shutting off the dryer and possibly the transport system during periods of processor inactivity. If the water flow rate is too slow, the mixing valve may not be able to maintain water temperature control, which will result in loss of developer temperature control. This would result in the over- or underdevelopment of the first films processed after the processor is put back into normal operation.

MISCELLANEOUS FILM PROCESSING CONSIDERATIONS

Other topics that should be covered in a comprehensive discussion of film processing are hypo retention levels, darkroom safelight levels, film and chemical storage conditions, and silver reclamation.

Hypo Retention

Hypo retention, or residual fixer, is a measurement of the amount of thiosulfate (fixer) remaining in the film emulsion after the film has been processed. High levels of residual fixer will lead to the appearance of a general brown stain on the film with time, the stain appearing more rapidly with higher levels of residual fixer. The level in a processed film is determined by a number of interrelated factors, including composition of developer (especially amount of film hardener), type and brand of film, composition of fixer, time in fixer, fixer temperature, time in wash, wash temperature, and wash agitation.

A residual fixer test in quite simple to conduct. Various film manufacturers sell kits or can supply the specific test protocol for this purpose. If the residual fixer level is too high, and the water flow rates have been checked and are correct, the film manufacturer and/or the processor service company representative(s) should be contacted.

Darkroom Safelight Levels

It is the subjective opinion of most people who work part-time in a darkroom that the light levels are too low. This is especially true of those people who are constantly moving from light areas to the darkroom. This impression often leads to placing bulbs of too great a wattage in safelights, and consequently to fogged film. Some suggestions for obtaining an adequately lighted darkroom are as follows:

1. Have the walls and ceiling painted white or off-white for maximum dispersal of available light.
2. Have light-colored countertops for maximum contrast between film, cassettes, and countertops.
3. Have indirect safelight(s) pointed towards the ceiling or walls for general illumination.
4. Have small safelights located over work areas as needed.
5. Follow the film manufacturer's recommendations for distances, locations, and wattages of bulbs.
6. Test the safety of safelights at least twice a year.

A safelight test should show that no additional density is added to an x-ray *exposed* radiograph when exposed to a minimum of two minutes of safelight (keep one-half of the film covered for comparison). Two minutes is chosen because it probably represents a maximum time that a radiograph might be exposed to a safelight in a darkroom before processing. The film used for the test should be previously exposed with intensifying screens to a level that will produce a density of from 0.5 to 1.0 above base-plus-fog. (If you remember from the characteric curve discussion, this is the level that has the greatest sensitivity, i.e., the largest film gradient. It is also the level at which most radiographs are produced.)

Safelight levels should also be checked whenever a new film type is added to the darkroom. This is especially true when rare earth intensifying screen systems are added to a department. These films are most sensitive to green light and require a different safelight filter than calcium tungstate screen films (which are most sensitive to blue light).

Storage Conditions

Sensitized photographic materials will slowly lose "activity" with time. This loss will result in an increase in the base plus fog level and a decrease in the average gradient and speed of the film. This degradation is accelerated greatly by storage at high temperatures, but is also accelerated by storage at high humidity, or by exposure to radiation sources or processing chemical fumes.

In general, film should be stored at 50-70°F and 40-60% relative humidity. It can be stored at lower temperatures (in fact film degradation will virtually stop below 0°F). However, if film is kept at lower temperatures, it must be brought to room-temperature equilibrium before the packaging is opened. This may take more than 24 hours for 100-sheet boxes that were kept below 0°F.

Processing chemicals should also be kept at 50-70°F but in a separate ventilated room. Chemicals cannot be kept at lower temperatures because some of the constituent parts will crystallize and will not redissolve even when the chemical is returned to higher temperatures.

Silver Reclamation

A silver reclamation system should be an integral part of a radiographic darkroom facility. The amount of money returned can pay a substantial portion of the cost of chemicals. In addition, there are established standards for the allowable concentration of various heavy metals that can be discharged into the sewer system. If enforced, these standards will require most radiology departments to have a silver recovery system.

There are two types of system available, the cartridge and the electrolytic system. The cartridge is loaded with steel wool and operates by the metallic replacement principle; the silver ion becomes solid metal and the iron goes into solution as an ion. The system has a low initial cost, requires no electrical installation, and requires very little effort to use. However, the silver sludge requires considerable refining, the unit allows only about 200 gallons of fixer to pass through before replacement is necessary, and it produces an effluent high in iron content, which can block the drain.

The electrolytic system involves the electrical plating of the silver on a cathode. This process has a higher efficiency for removing silver than the cartridge system, yields silver of a high purity, and can handle large amounts of fixer without changing. However, it has a higher initial cost, requires electrical power, and requires more frequent monitoring than the cartridge system.

SUMMARY

Film processing in radiology is responsible for converting a nonvisible "latent image" carrying information about the internal structure of a patient into a visible permanent display of that information. Variations in the processing parameters will change the ultimate visualization of that information by affecting both the contrast and the overall "darkness" of the film. In order to eliminate film processing as a variable in the radiographic imaging process, it is essential to establish and maintain an automatic film processing quality assurance program. Such a program will consist of the production (or purchase) of sensitometric control strips, the processing and measurement of those strips, the measurement of processor operating values, the evaluation of the resultant data, and the performance of any indicated corrective action. The faithful operation of such a quality assurance program will result in uniformly and optimally processed radiographs, and will eliminate processing as a cause of improper diagnoses and unnecessarily repeated radiographs.

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LABORATORY EXERCISE 6

QUALITY ASSURANCE OF AUTOMATIC FILM PROCESSING

Variations in processing conditions can have a dramatic effect on image quality. However, automatic processing should not be a variable in the radiographic process but should be controlled to remain *constant,* so that it will have no variation in effect on different radiographs. This exercise utilizes the principles of a processor quality assurance program to investigate the standardization of a radiology department's film processors.

Equipment

This exercise requires the use of the following equipment:

Radiographic film
/ Sensitometer
-or-
Small teaching x-ray machine
Aluminum stepwedge
Cassette with par speed screens
Densitometer

Procedure

1. Using the sensitometer, expose a sheet of film and process it immediately. Record the date, time, and location of the processor on the film. Repeat this procedure for each processor in the department. NOTE: It is important to use film from the *same* box for all of these exposures so that variations in emulsion will not affect the results. *Or,*

2. If you do not have a sensitometer available, a less desirable alternative is to make x-ray exposures of the stepwedge, using the following exposure parameters:

kVp — 80
mAs — 9
Filtration — 2.5 mm Al added
Diaphragm — none
Cassette — 8 × 10 inch, par speed screens

As in part 1, expose, immediately process, and label one film for each processor in the department. In this case, be sure to use the *same* cassette and film from the *same* box for each exposure. Also, check the kVp and mAs and position the cassette and stepwedge carefully in exactly the same way for each exposure so that no unnecessary variables are introduced.

3. Compare the processed films visually and densitometrically and note the differences.

4. Record the following data for the film from each processor:

a. Base plus fog level

b. Speed indicator — The actual density of the step closest to 1.00 above base plus fog. (Use the same two steps for all films.)

c. Contrast indicator — The density difference between the step closest to 2.00 above base plus fog and the step closest to 0.25 above base plus fog. (Use the same two steps for all films.)

Ideally all processors in a department should operate at the same level sensitometrically. Therefore, all of the processors you evaluate should produce films with base plus fog measurements within a range of ±0.05 density units of the average; the speed and contrast indicators should be within a range of ±0.10 density units of the average.

QUESTIONS

1. From an examination of the radiographs obtained, does it appear that a processor quality assurance program has been implemented in this particular diagnostic radiology department? If not, is one needed? If so, is it successful?
2. How would you account for the variations, if any, noted in parts 3 and 4?

7

GEOMETRIC FACTORS IN RADIOGRAPHY

The x-ray intensity of the beam that emerges from the tube varies greatly throughout the cone of emergent radiation. Not only does the intensity vary with the distance from the focal spot, it also varies throughout the film plane. The choice of source-image receptor distance is an important matter since, along with some factors inherent in x-ray system design, this distance affects the "sharpness," the magnification, and the distortion of the image; the field uniformity; and the patient dose.

BASIC GEOMETRIC PRINCIPLES

The Law of Similar Triangles

In order to properly discuss many of the concepts presented in this chapter, it is necessary to utilize some basic geometric principles which will be briefly reviewed in this section. Two triangles that have the same shape (technically the three angles of one are equal to the three angles of the other) but different sizes are said to be *similar triangles*. Corresponding sides or altitudes of similar triangles are proportional. Similar triangles are often encountered in radiography, as depicted in Figure 7-1.

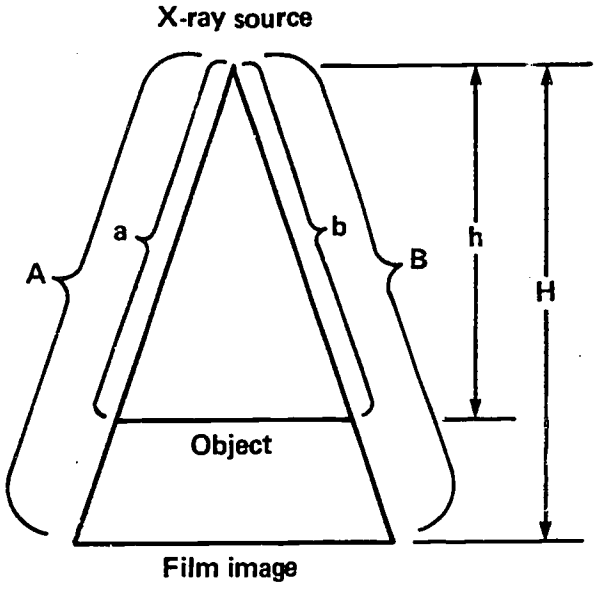

Figure 7-1. The geometrical basis of radiography.

The proportionality of equivalent dimensions of the two triangles (focal spot-to-object and focal spot-to-image receptor distances) results in the following relationship:

$$\frac{h}{H} = \frac{a}{A} = \frac{b}{B} = \frac{\text{object size}}{\text{image size}} \qquad (1)$$

(The object of interest and the image plane must be parallel for this relationship to be true.) This "law of similar triangles" will appear throughout this chapter.

Inverse Square Law

The inverse square law is applicable to any electromagnetic radiation coming from a point source — infrared, light, radio waves, x rays, or gamma rays. This is strictly a geometric phenomenon; it has nothing to do with the interaction of radiation with matter. This "law" is based on the fact that the photons emitted from a point source travel radially away from the source; i.e., the photons "spread out" as they get further and further from the source. Therefore the number of photons per unit area and consequently the intensity of the radiation decreases as the distance increases. Note, however, that the *total energy* in the radiation beam is conserved (the law of conservation of energy).

Consider a square beam of energy(1) emitted at a rate of E/sec, passing through square areas ABCD and EFGH, as illustrated in Figure 7-2. The two square areas have sides of lengths S_1 and S_2 and are at distances of d_1 and d_2 from the focal spot, respectively.

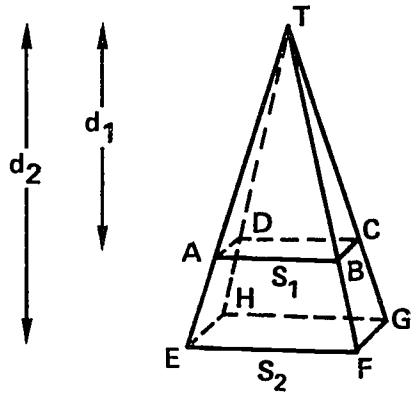

Figure 7-2. Inverse square law.

Intensity is defined as the total energy passing through an area per unit area per second. Therefore, for square ABCD,

$$I_1 = \frac{E/sec}{(S_1)^2} \quad (2)$$

and for square EFGH,

$$I_2 = \frac{E/sec}{(S_2)^2} \quad (3)$$

Thus, by dividing I_1 by I_2,

$$\frac{I_1}{I_2} = \frac{\frac{E/sec}{S_1^2}}{\frac{E/sec}{S_2^2}} = \frac{S_2^2}{S_1^2} \quad (4)$$

but by similar triangles TAB and TEF

$$\frac{S_1}{S_2} = \frac{TA}{TE} \quad (5)$$

and by similar triangles TAC and TEG

$$\frac{TA}{TE} = \frac{\text{altitude of TAC}}{\text{altitude of TEG}} = \frac{d_1}{d_2} \quad (6)$$

Consequently

$$\frac{TA}{TE} = \frac{S_1}{S_2} = \frac{d_1}{d_2} \quad (7)$$

and

$$\frac{S_1^2}{S_2^2} = \frac{d_1^2}{d_2^2} \quad (8)$$

so that

$$\frac{I_1}{I_2} = \frac{d_2^2}{d_1^2} \quad (9)$$

This is the ***inverse square law***. It applies to any electromagnetic radiation from a point source. A basic understanding of this concept is necessary for various calculations. including technique conversion to non-standard distances, and dose calculations. For example, if it is known that the exposure rate is 1 R per hour at one meter from a point source, the rate at two meters would be

$$\frac{1^2}{2^2} \times 1 \text{ R/hr} = \frac{1}{4} \text{ R/hr.}$$

The inverse square law is based on the assumption that there is no energy absorption between the two distances and that the source is truly a point source. Very low kVp and very lightly filtered beams may have significant losses due to air absorption, and in such cases, the inverse square law will not be strictly valid.

One consequence of the inverse square law is that beam intensity varies more rapidly with small distance variations at short source-image receptor distances (SID) than at large ones. Therefore, for equal amounts of radiation reaching the film, the exposure at the skin of a patient will increase as the SID is decreased. (With a patient 6 inches thick, the skin dose will be 5% greater at 36 inches and almost 50% greater at 20 inches, as compared to the skin dose at 40 inches. This, of course, assumes that the mAs is adjusted so that the film is exposed equally in each instance.)

MAGNIFICATION OF THE IMAGE

Since the x-ray beam is generated at a point and is divergent from there, the radiographic image is always larger than the object being imaged. The physical situation is depicted in Figure 7-3.

Magnification is defined as the size of the image (i) divided by the actual size of the object (o). By similar triangles, magnification can be expressed mathematically as:

$$M = \frac{i}{o} = \frac{SID}{SID - OID} = \frac{1}{1 - \frac{OID}{SID}} \quad (10)$$

where SID = source-image receptor distance
and OID = object-image receptor distance

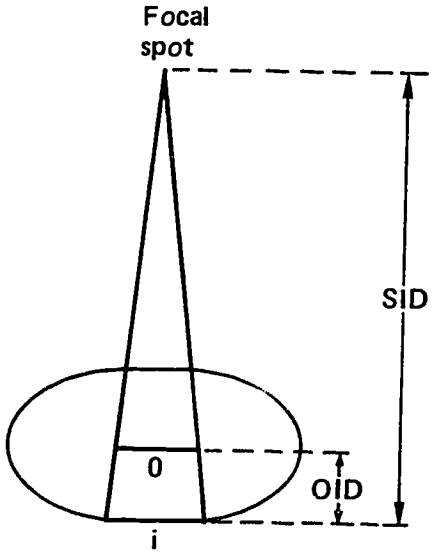

Figure 7-3. Magnification.

Notice that magnification depends on the relative value of the OID compared to the SID. Therefore, the amount of magnification can be decreased by either increasing the SID or decreasing the OID (the latter is often not possible). This effect is summarized in Table 7-1.

Table 7-1. MAGNIFICATION FACTORS

OID (inches)	SID (inches)		
	20	40	72
6	1.43	1.18	1.09
12	2.50	1.43	1.20

It should be noted that the magnification factor applies to the entire plane that is parallel to the film plane. The magnification formula is based only on vertical distances (SID and OID are measured perpendicularly to the film plane) and not on lateral displacements along the film plane. Therefore, the image of any object parallel to the film plane will be magnified, but the shape of the image will be identical to the shape of the object (see Fig. 7-4).

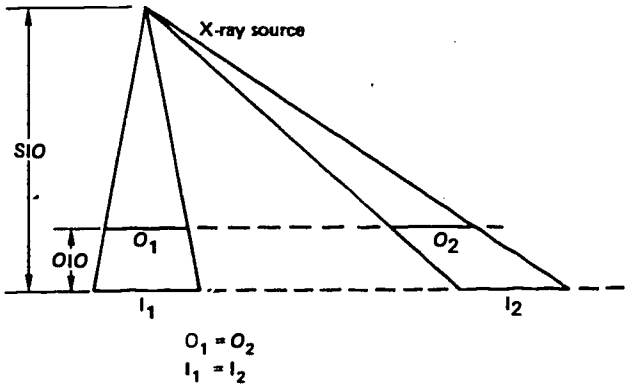

Figure 7-4. Magnification is independent of lateral positioning.

DISTORTION OF THE IMAGE

In itself, magnification is not a serious problem since the films can still be interpreted and, if needed, measurements from the film can be converted to actual values. However, in actual practice the objects being radiographed are three-dimensional and consequently lie in a range of distances from the film. As a result, the magnification varies throughout the object. This variation in magnification results in *distortion* of the size and shape of the image.

For example, consider a flat circular object that is not parallel to the film plane. The portion of the object farthest from the film will be magnified much more than the portion closest to the film. Therefore, the shape of the image will be distorted. The image of the circular object will be egg-shaped, its exact size and shape depending upon the amount of tilting.

A further consideration in the amount of distortion is the position of the object in the x-ray field, i.e., the lateral displacement of the object from the center of the field. Figure 7-5 illustrates how the image of a tilted two-dimensional object can differ. Thus, the amount of distortion depends upon both the amount of tilting and the lateral positioning of the object.

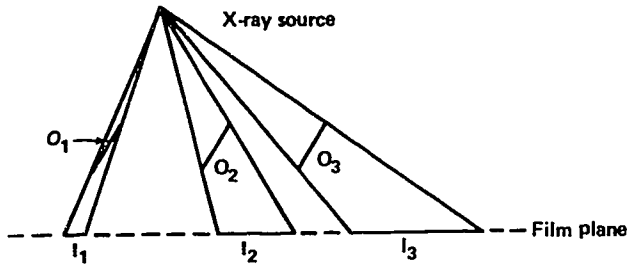

Figure 7-5. Distortion of the image of an object not parallel to the film plane.

The preceding figures have dealt with two-dimensional objects because the distortion effects are easier to visualize. However, because the objects radiographed in practice are three-dimensional, the problems of distortion are compounded. Figure 7-6 shows the situation when a sphere is radiographed in different locations in the x-ray field. If a line is drawn between the points where the rays are tangent to the sphere, the amount of distortion can be determined by the "tilt" of that two-dimensional object with respect to the film (i.e., the image of a sphere in the center of the x-ray field will be circular, but the image of a sphere anywhere else in the field will be egg-shaped).

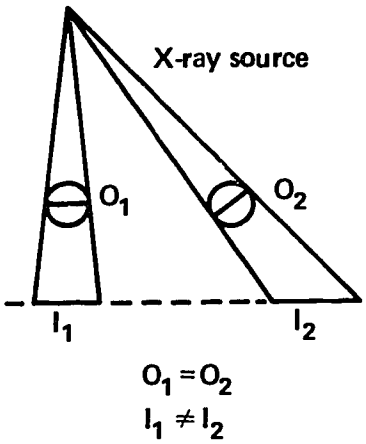

Figure 7-6. Distortion of the image of a sphere.

One other type of distortion involves the relative positions of two objects at different distances from the film. The two objects may be imaged as superimposed or separated, depending upon their lateral positioning in the x-ray field (Fig. 7-7). This effect can be minimized by minimizing the overall magnification and also by placing the structures of interest as close to the center of the x-ray field as possible.

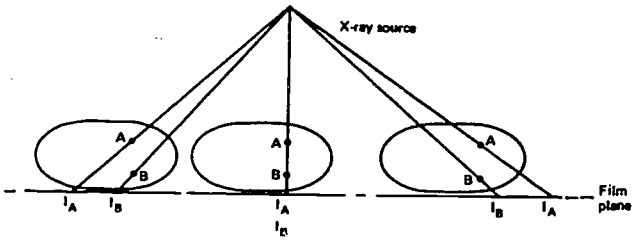

Figure 7-7. Distortion of the position of two internal structures.

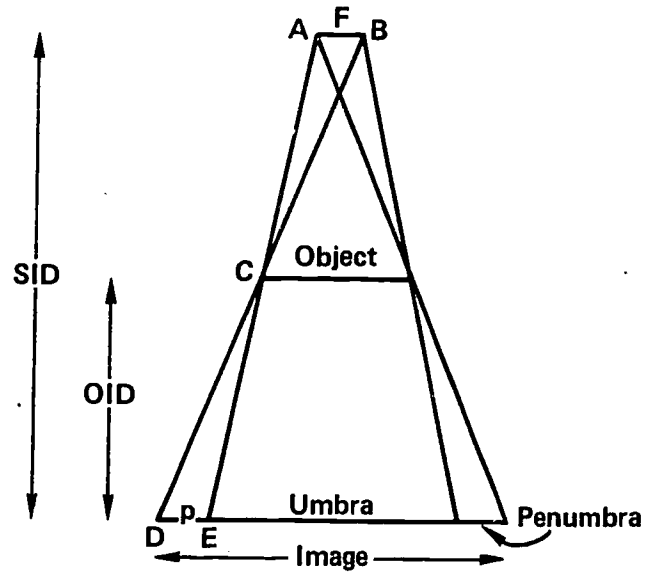

Figure 7-8. Geometrical unsharpness.

IMAGE UNSHARPNESS

There are many factors that contribute to the "unsharpness" or loss of detail in a radiographic image. The major causes of unsharpness are usually subdivided into four categories: geometric unsharpness, absorption unsharpness, motion unsharpness, and screen unsharpness. The geometrical bases for these effects will now be discussed.

Geometric Unsharpness

In previous discussions and figures, the x-ray source has been idealized as a "point source." Although this assumption is valid for the situations already discussed, the finite size of the source must be considered when evaluating the detail that can be obtained in any given radiographic situation. The detail loss due to *penumbral effects* (which is the effect encompassed by the term "geometric unsharpness") is often the limiting factor in radiographic resolution.

Since the radiation is emitted from a focal "area" rather than a focal "spot," the edge of an object will not be imaged as a sharp distinction between radiographic shadow (umbra) and full exposure, but rather as a region of partial shadow called penumbra. Geometrical unsharpness is illustrated in Figure 7-8. The film exposure across the penumbral region is not constant, since the penumbral region immediately adjacent to the umbra (E) receives radiation from only a small portion of the focal spot, while a region on the outer side of the penumbra (D) receives radiation from almost the entire focal spot.

The width of the penumbra (p) can be calculated by the use of similar triangles CAB and CDE:

$$\frac{p}{F} = \frac{\text{altitude of CDE}}{\text{altitude of CAB}} = \frac{OID}{SID\text{-}OID} \qquad (11)$$

and

$$p = \frac{(F)\ (OID)}{(SID\text{-}OID)} \qquad (12)$$

Thus, as in the case of magnification, increasing the SID or decreasing the OID will decrease the size of the penumbral shadow. Those structures closest to the film will be sharper than those closest to the tube. The penumbra can also be reduced by using a smaller focal spot, if available. The size of the penumbra under various conditions is summarized in Table 7-2.

Table 7-2. SIZE OF PENUMBRA (in mm) FOR A 1.0 × 1.0 mm FOCAL SPOT

OID (inches)	SID (inches)		
	20	40	72
6	0.43	0.18	0.08
12	1.50	0.43	0.20

An added complication of penumbral unsharpness is that it is not constant across the film, but depends upon the location in the field with relation to the anode and the cathode. As discussed in Chapter 1, the anode in a diagnostic tube is generally positioned at an angle of 20

80

degrees from the vertical. (The reason for this orientation is to increase the actual area of the focal spot for heat dissipation purposes, while allowing a small effective focal spot.) The effective focal spot size specified by manufacturers is determined along the central ray. Actually, however, for a given x-ray tube, the effective focal spot size varies throughout the x-ray field, decreasing on the anode side of the central ray and increasing on the cathode side. The variation in effective focal spot size and its effect on penumbra is illustrated in Figure 7-9. The magnitude of this effect is considerable. A 17-inch film exposed at 40 inches using an x-ray tube with an effective focal spot length of 1.0 mm will "see" effective focal spot sizes of 0.41 mm and 1.6 mm at the anode and cathode ends of the film respectively. (For an

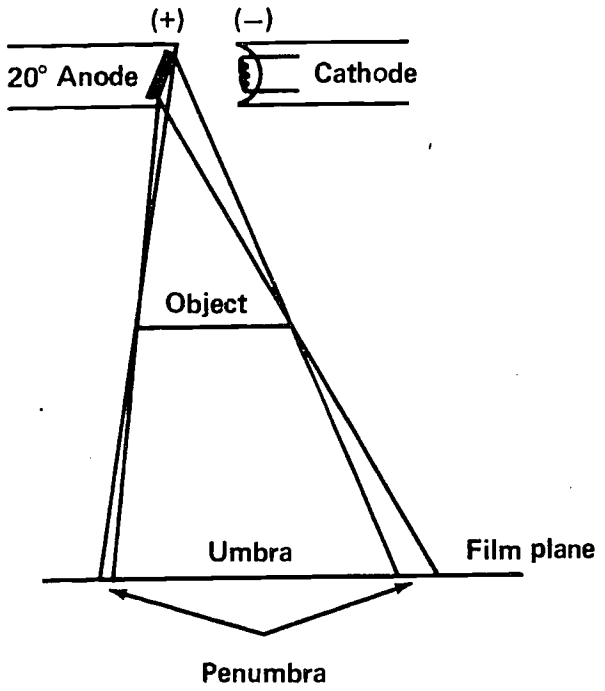

Figure 7-9. Effective focal spot size vs. penumbra.

object 6 inches above the film at a SID of 40 inches, the penumbra would be 0.07 mm, 0.18 mm, and 0.27 mm at the anode end, center, and cathode end of the 17-inch film.) Therefore, in critical examinations, the structure of greatest interest should be placed towards the anode. Quite obviously this effect is more evident with greater amounts of magnification or on the periphery of films at shorter SID's, because the angular dispersion of the beam is greater at shorter distances.

Absorption Unsharpness

Absorption unsharpness is a term that is used to describe the unsharpness in the image due to variations in absorption throughout a three-dimensional structure, caused by the particular ***shape*** of that structure. Once again assuming a point source of radiation, absorption unsharpness is depicted in Figure 7-10A. The three figures are the frustum of a cone, a cube, and a sphere (in specific locations in the x-ray beam).

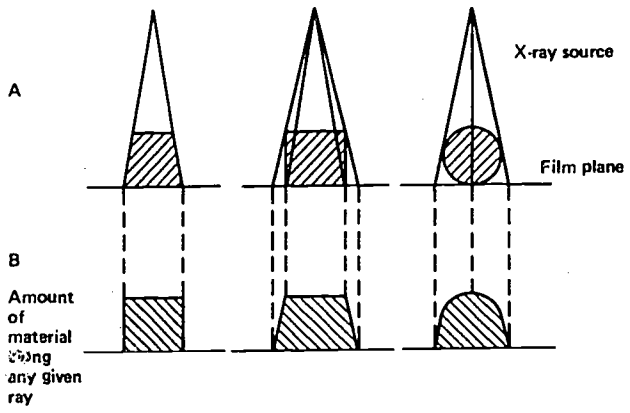

Figure 7-10. Absorption unsharpness.

The image of the frustum will be the most distinct because the edge of the cone lies along the path of the x rays. The physical basis for this phenomenon is the differing amounts of material that are interposed across the x-ray beam by the various shapes. This is illustrated in Figure 7-10B(2). The cube will show absorption unsharpness at its edges because of the decreased material in the path of the x rays that pass through the sides of the cube. The path length through the sphere changes across the entire object with a maximum at the middle. These three examples were specifically chosen to illustrate extreme situations. If the objects were positioned differently, the effects would be entirely different. For example, if the edge of the cube were located along the central ray, the image of that edge would be sharp, but if the frustum were in that position, it would show unsharpness on both edges. Absorption unsharpness will occur with just about every object radiographed. Most structures in the body are rounded and so this effect is rather significant. Since penumbral effects are operating simultaneously with the absorption effect, the exact boundary of many internal structures will be indistinct.

Motion Unsharpness

Motion unsharpness in the image is caused by movement of the patient or the x-ray tube. The effect of motion on the image is depicted in Figure 7-11. The primary methods of decreasing motion unsharpness are the use of shorter exposure times or the use of patient-immobilizing devices. Although motion unsharpness can be caused by movement of the x-ray tube, the effect is much less than for equal movements of the patient, unless there is considerable magnification present.

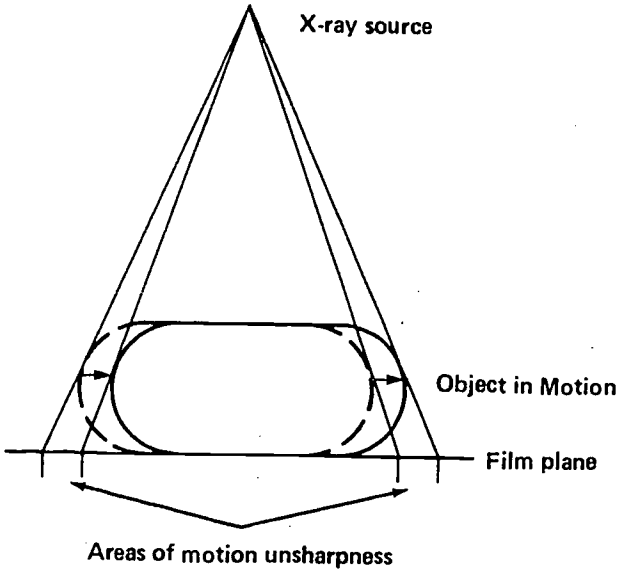

Figure 7-11. Motion unsharpness.

Screen Unsharpness

The effect of intensifying screens on the sharpness of the radiographic image was discussed in Chapter 4. In summary, it was shown that the radiographic sharpness is dependent upon the size of the fluorescent crystals, the thickness of the intensifying screen, and the closeness of contact between the film and the intensifying screens.

Total Unsharpness

All four types of unsharpness will be present in any radiograph and will contribute to the overall detail visibility. In most cases, the total unsharpness is predominantly due to either geometric unsharpness or screen unsharpness (when using higher speed screens). The best method of evaluating the resolution ability of an imaging system is with the use of the modulation transfer function (MTF)(3). (A discussion of MTF will be left to more advanced textbooks.) Suffice it to say that efforts should be made to keep all types of unsharpness to a minimum whenever warranted. For example, if a machine with a 2.0 mm by 2.0 mm focal spot is being used, the geometric unsharpness will be such that nonscreen techniques will not yield any better definition than detail screen techniques. Likewise, magnification techniques increase the penumbra (see equations 10 and 12) so that nonscreen techniques may be a waste of patient exposure, depending on the amount of magnification. With a magnification of 2, the penumbra will be equal to the focal spot size. Consequently, large magnification techniques are only practical with microfocus x-ray tubes (focal spot sizes less than 0.5 mm). However, with small focal spots, the heat loading will limit the possible exposures. An incidental benefit of the magnification technique is a decrease of scattered radiation reaching the film because of the air gap; however, the patient dose is increased significantly because of the decreased object-image receptor distance.

FIELD UNIFORMITY: THE HEEL EFFECT

Up to this point, we have assumed that the output of an x-ray tube is uniform across the radiation field. Unfortunately, this is not true for a variety of reasons, the most important being the so-call ***heel effect.*** This effect is a consequence of the angle of the target of the tube. Most x-ray photons result from interactions that occur at a depth within the target, not on the surface. Those photons that are emitted in a direction nearly parallel to the target surface must necessarily pass through more material before escaping from the target as compared to those emitted more perpendicularly. Consequently, the portion of the beam towards the anode will be attenuated more than the portion towards the cathode, resulting in a diminished intensity toward the anode with a sharp cutoff at the target angle.

Two other factors contribute to the nonuniformity of the radiation field at the film. The first is based on the "inverse square law." Since the x-ray source is roughly a point source, the SID is not constant across a flat film but is greater along the film boundaries in a normal view. For a 14" × 17" film at 40 inches, this phenomenon yields a 7% decrease in intensity at the corners when compared to the center of the film. This effect is circularly symmetrical about the central ray.

The second factor involves an increase in filtration for some of the beam. Except for the central ray, the beam must pass obliquely through the filters placed in its path. For the 14" × 17" film at 40 inches, the increase in filtration from the center of the film to the corner is almost 4%. The effect of this increase depends upon the kVp and the filtration already present in the beam. This effect is also symmetrical about the central ray.

All of these factors operate simultaneously and cannot be easily separated. Therefore, they are commonly lumped together under the label ***heel effect.*** The intensity variations due to this total "heel effect" are illustrated in Figure 7-12. A 17-inch film is depicted at 40 and 72 inches to show the magitude of this effect. At 40 inches there is about a 30% intensity difference from one end to the other (73% to 105%) while at 72 inches the difference is much less (87% to 104%). Clearly, the consequences of the heel effect can be reduced by utilizing only the central portions of the beam. This can be accomplished by either reducing the field size or by increasing the SID. In cases where the heel effect will be a factor, the patient should be aligned with the more easily penetrated area toward the anode; this is most commonly done when radiographing the thoracic spine. The tube should be oriented with the anode over the upper thoracic

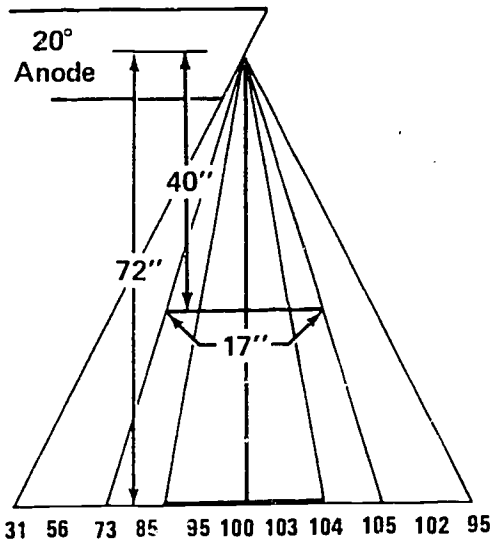

Figure 7-12. The heel effect.

spine and the cathode over the lower thoracic spine where the thicker body structures will receive the increased exposure.

LOCALIZATION OF THE FOCAL SPOT

Throughout this chapter the SID and the OID have appeared frequently in various formulae and must be determined if quantitative information is desired. In order to determine the SID, the location of the focal spot within the tube head must be known. Most machines have the location of the focal spot marked on the outside of the tube housing and/or have a scale for measuring the SID (or the focal spot-table top distance). If these values are not provided with the machine or if you wish to check them, they can be easily determined. A simple and accurate method utilizes two pinholes in a single plate (Fig. 7-13). The plate is radiographed with the film positioned at a known distance (d_2) below it. The focal spot to plate distance (d_1) and the SID ($d_1 + d_2$) can then be determined as follows:

If: b_p = the distance between the centers of the pinholes
b_i = the distance between the centers of the images
d_1 = the distance between the focal spot and the pinhole plane
d_2 = the distance between the pinhole and film planes (the two planes must be parallel)

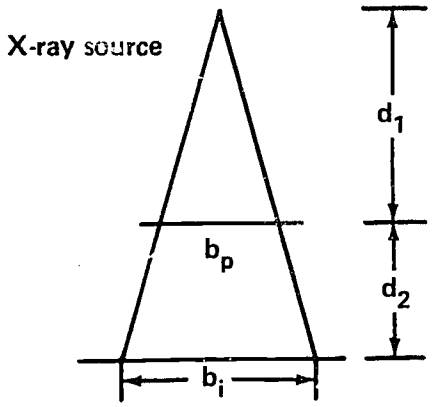

Figure 7-13. Dual pinhole camera.

then by similar triangles:

$$\frac{b_i}{b_p} = \frac{SID}{d_1} = \frac{d_1 + d_2}{d_1} = 1 + \frac{d_2}{d_1}$$

and solving for d_1 gives:

$$d_1 = \frac{d_2 b_p}{b_i - b_p}$$

A short piece of metal can be substituted for the two pinholes. The accuracy of the result may be slightly less because of the thickness of the metal, but it is easier to do and the geometric derivation is exactly the same (the length of the metal = b_p).

SUMMARY

Simple geometric relationships can be used to help determine the size, shape, and sharpness of the radiographic image. The image of an object will always be magnified, the exact amount of the magnification depending on the source-image receptor distance (SID) and object-image receptor distance (OID). Since nearly all objects radiographed in clinical practice are three-dimensional, the magnification will vary throughout the object resulting in a distorted image. The sharpness of the image depends on the actual size of the focal spot; the size, shape, and orientation of the object; movement of the object; and the geometrical configuration of the intensifying screens used. The angle of the tube anode causes uneven sharpness across the film plane and also contributes to uneven x-ray intensity levels throughout the field—a phenomenon known as the "heel effect."

REFERENCES AND NOTES

1. The energy can be projected with any cross-sectional plane shape (square, circular, irregular, etc.) by suitable restriction of the beam, such as lead shutters in an x-ray machine collimator.
2. The increase of absorption material due to the increase in path length of the oblique rays has been ignored in this simple diagram.
3. See Ter-Pogossian, Michel M., *The Physical Aspects of Diagnostic Radiology*, Harper & Row, Hoeber Medical Division, New York, 1967, pp. 241-249.

LABORATORY EXERCISE 7

GEOMETRIC FACTORS IN RADIOGRAPHY

The intensity of an x-ray beam varies greatly throughout the cone of usable radiation emerging from the x-ray tube. The choice of a specific source-imaging system distance (SID) in any technique must be carefully considered since the final choice affects the patient dose, image magnification, image distortion, image "sharpness," and field uniformity.

The purpose of this laboratory exercise is:

1. To determine the SID in actual practice,
2. To investigate the effects of variation of SID on magnification, magnification distortion, and penumbra,
3. To illustrate the "heel effect."

Equipment

This exercise is to be conducted in the Radiological Health Sciences Learning Laboratory and will require the following items of equipment:

Small teaching x-ray machine
Assortment of lead diaphragms
Assortment of aluminum filters
Magnification shelf
Cardboard exposure holders
Cassettes with various speed screens
Radiographic film
Radiographic hand phantom

Procedure

1. Determination of the SID

Using a small piece of thin metal about 2 inches long, determine the SID for shelf 5. Place the plastic shelf with the object at shelf level 1 and the film on shelf 5. Remember that the length of the object and the distance between the object and the film must be accurately known. Suggested exposure parameters:

kVp — 80
mAs — 20
Filtration — 2.5 mm Al added
Diaphragm — none
Cardboard exposure holder, 8 × 10 inch

2. Magnification

a. Make two exposures of the magnification phantom on a single sheet of film, using the following exposure parameters:

kVp — 60
Filtration — 2.5 mm Al added
Diaphragm — none
Cassette — 8 × 10 inch, par speed screens

Exposure 1: Shelf 3, 14 mAs
Exposure 2: Shelf 5, 60 mAs

This phantom contains identical circular objects at 5 cm intervals from 0 to 20 cm depth. The size of the objects relative to one another will be distorted by different amounts of magnification. (You may wish to make additional exposures with this phantom in different positions in the x-ray field to illustrate the distortion of the position of objects at different depths.)

b. Determine the size of a diaphragm to be used in the upper diaphragm filter slot that will give a field size of 8 × 10 inches at shelf 5. Use any method that you feel will solve the problem, but record your method and results.

3. Distortion

Using the exposure parameters from part 2a (shelf 3) make a radiograph of the distortion phantom, which contains various objects in different orientations. If there are any objects that you cannot identify, make a lateral exposure.

4. Unsharpness

a. Make one radiograph of the hand phantom using the following exposure parameters (conventional technique):

kVp — 60
mAs — 100
Filtration — 2.5 mm Al added
Diaphragm — 3 inch diameter
Distance — shelf 5
Cardboard exposure holder

Make a second exposure using a magnification technique, i.e., place the hand phantom on the plastic shelf at level 3 and the film on shelf 5. Also place some measured object on the shelf so that the magnification can be calculated. Examine the films for a qualitative measure of unsharpness.

b. Make 2 sets of similar films (conventional technique and magnification technique) with detail screens (24 mAs) and with high speed films (3 mAs). Examine these films for unsharpness and compare them with the films of part 4a.

5. Heel Effect

To demonstrate the "heel effect" make the following radiograph with no object in the beam:

kVp — 60
mAs — 1
Filtration — none
Diaphragm — none
Distance — shelf 3
Cardboard exposure holder

Be sure to use lead markers to identify right-left and front-rear on your film.

Although exposing a film without any added filtration is admittedly a contrived situation (additional filtration tends to diminish the heel effect), an effect of this magnitude is not uncommon in the normal useful beam of many x-ray machines.

QUESTIONS

1. What is the SID for shelf 5? Show your calculations.
2. From the films of part 2a, determine the magnification at 20 cm above the film for the two different shelf heights.
3. What accounts for the difference in appearance of one of the identical objects in each of the images in part 2a?
4. What is the diaphragm size determined in part 2b?
5. When the magnification on a certain film must be determined a "magnification ring" is generally used. Why is the circular shape specifically used for this purpose?
6. You wish to obtain a posterior pelvis radiograph at 36 inches SID but the only technique chart shows 120 kVp, 10 mAs at 40 inches. What mAs do you tell your technologist to use?
7. From the film in part 5, where are the anode and cathode located in terms of the cabinet of the teaching x-ray machine?
8. For a radiograph of the thoracic spine, how should the patient be oriented with respect to the cathode and anode? Why?

8

X-RAY QUALITY ASSURANCE

The sequence of events that occur in the production of a radiograph in an "ideal" radiology department is:

1. Measure the thickness of the patient.
2. Consult the technique chart based on that particular thickness to obtain the technique factors, including kVp, mAs, distance, grid (if any), and speed of intensifying screens.
3. Using any of the appropriate x-ray units in the department, position the patient.
4. Set the technique factors from (2).
5. Expose the radiograph.
6. Using any of the processors in the department, process the film.

The resultant radiograph should be optimally exposed, optimally processed, and consequently should be easily interpretable by the radiologist (at least from a technical standpoint). The determination of technique factors based on thickness measurements will provide good results in a very high percentage of cases. Exceptions to this occur, such as the case of a thick abdomen that is greatly distended with air due to a bowel obstruction. Fortunately, however, the film-screen imaging system has a great deal of latitude so that most normal and abnormal anatomical variants will yield a readable (although perhaps not optimal) image.

If all of the above is true, then why are the reported retake rates as high as 10%, or more(1)?

In general, retake reasons can be divided into two categories: personnel errors and technical errors. *Personnel errors* include the following: incorrect positioning, failure to measure the patient, use of the incorrect technique factors, improper collimation, and the use of incorrect accessory hardware (grids, screen speed and/or type, etc.). The reduction of these personnel errors must take place through technological education, a topic beyond the scope of this text.

Technical errors are those caused by the improper functioning of the radiological hardware. These include such problems as inaccurate kVp, mA, and timer stations; dirty and/or damaged film cassettes; improperly installed, bowed, or damaged grids; malfuctioning beam limitation systems; improper film storage and handling; and inconsistent or improper film processing.

Clearly, if the x-ray output varies from day to day or from room to room while using the same technique settings, or the processing varies substantially during the course of the workday, even the best-trained, most conscientious technologist will not be able to produce consistent films. It is the purpose of a quality assurance program to reduce these technical errors to a level such that they will not necessitate a retake examination.

Table 8-1 summarizes the results of a study into the causes of retakes in two large hospitals, one a community hospital, the other a major metropolitan teaching hospital. The major cause of retakes (over- or underexposure) may be the result of either personnel or technical errors. This chapter will cover quality assurance of the x-ray generator and some of the accessory hardware. It will not cover those topics already covered in previous chapters: processors (Chap. 6), film storage and handling (Chap. 5), darkroom illumination (Chaps. 5 and 6), and dirty and/or damaged cassettes (Chap. 4).

Table 8-1. CAUSES OF RETAKES IN TWO LARGE HOSPITALS(2)

REASON	PERCENT OF RETAKES	
	1000 BED TEACHING HOSPITAL	600 BED COMMUNITY HOSPITAL
Film too dark or light	34	44
Position error	31	23
Respiratory motion	14	6
Other motion	6	4
Collimator cut	4	2
Other reasons	9	9
Multiple reasons	2	10
Not given	1	2
Total	100	100
Overall Retake Rate	3.9%	5.3%

GENERAL CONSIDERATIONS OF AN X-RAY QUALITY ASSURANCE PROGRAM

The Standard Technique Chart

A specific goal of the processor quality assurance program (discussed in Chap. 6) was to have all of the processors in a department matched to produce the same sensitometric results. In this way, any departmental processor could be used and identical results would be

obtained. Likewise, an idealized goal of an x-ray quality assurance program would be to have all of the departmental x-ray units carefully matched. Then there could be one *standard technique chart* that could be used throughout the department. However, from a practical viewpoint this would be almost impossible to achieve. Frequent and deliberate miscalibrations would have to be made to account for differences between units. A simpler solution is to have slightly different technique charts for each room (designed to provide the same radiographic results) and assign technologists to specific rooms, rather than rotating them between rooms.

The Individual Room Log

In carrying out a quality assurance program it is important to keep accurate records of all test results as well as all modifications made. An *individual room log* should be maintained for each x-ray unit in the department. This room log should be kept with the unit so that all personnel involved (technologist, radiologist, equipment service personnel, and physicist) can have ready access to it. The room log should contain the following information:

1. Equipment data
   a) Identification of major components
      1) Manufacturer
      2) Model number
      3) Serial number
      4) Date installed
   b) Technical specifications (such as single or three phase, focal spot size, mA and kVp stations, etc.)
   c) Tube heat loading charts
   d) Equipment operating instructions
2. An outline of the quality assurance program
3. A log of quality assurance tests
   a) Specific test performed
   b) Date performed
   c) Test results
   d) Individual performing test
4. A log of all service work
   a) Malfunction
   b) Service performed
   c) Date of service
   d) Individual performing service

SPECIFIC QUALITY ASSURANCE TESTS

The specific tests discussed here are primarily those related to the quantity and quality of the x-ray output for radiographic units. These are also generally applicable to fluoroscopic units; however procedures applicable only to fluoroscopic units (such as automatic brightness control tests) are not discussed.

Exposure Time

The total x-ray output is directly proportional to the time of exposure. Therefore incorrect or nonrepetitive exposure times will lead to inconsistent radiographs. There are three general types of systems used for measuring exposure time:

Oscilliscope monitoring. This system utilizes a small solid state radiation detector that is placed directly in the x-ray beam. The output of the detector is fed into a storage oscilliscope or a regular oscilliscope with an instant camera attached for data retention. In addition to providing a total time measurement, the actual output waveform can be analyzed to provide additional information such as the amount of ripple in a three phase unit, or the presence of extraneous x-ray pulses generated at the initiation or termination of exposure.

Exposure time monitors. There are several timer units commercially available that are placed directly in the x-ray beam. These units read out the number of pulses of x-ray output for half-wave and full-wave rectified single phase units, or a total exposure time for three phase units. (As discussed in Chap. 1, half-wave rectification produces 30 pulses per second, full-wave rectification produces 120 pulses per second, and three phase x-ray generators provide a continuous output with a 3 to 20% voltage "ripple" below the maximum applied voltage.)

Spinning tops. These tops are x-ray opaque except for a small hole or slit. For a single phase unit, the top is set spinning and an exposure of the spinning top is made on film; the resulting image will consist of a series of spots corresponding to each x-ray pulse. Since there are no pulses with a three phase unit the top should be rotated at a precise speed (usually with a synchronous motor) while the film exposure is made; in this case the angle of the exposed arc is proportional to the exposure time.

Peak Tube Potential (kVp)

The kVp is the most important operating parameter of an x-ray system. The kVp applied to the tube primarily determines the contrast of the resultant image. In addition, minor variations in kVp will produce major changes in the total amount of radiation reaching the film. Every kVp level that is used should be checked and adjusted so that the actual kVp is within ±4 kVp of the indicated kVp. A department should avoid having kVp correction factors at the machine (i.e., to get 80 kVp, set dial at 74 kVp). Such factors tend to be ignored and therefore lead to retakes. Most machines can be adjusted by service personnel so that actual and indicated kVp agree.

The easiest way to accurately determine the kVp is by using a special test cassette based on the principles first demonstrated by Ardran and Crooks(3). This test cassette operates as illustrated in Figure 8-1. The incident x-ray beam is heavily filtered to remove almost all of the

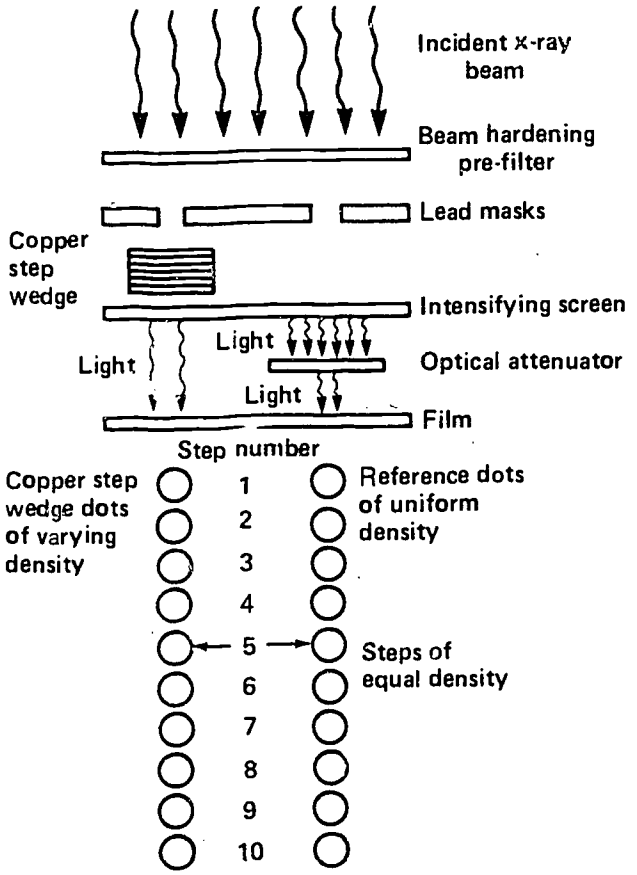

Figure 8-1. Principle of operation of a test cassette for measuring the kVp of an x-ray tube(4).

low energy photons. A portion of the remaining beam passes through a copper stepwedge and is then imaged with a screen-film system. The other portion of the beam falls directly on the intensifying screen but the fluoroscent light emitted is reduced by interposition of an optical filter. The optical densities on the processed film are studied and the density of that particular step of the copper stepwedge which most closely matches the density of the optically reduced spot is found. A table of kVp versus the matched step number is provided. The various manufacturers of these cassettes claim an accuracy of ±2 to 4 kVp. Cassettes are available for various kVp ranges from as low as 25 kVp to as high as 150 kVp.

A second method of determining kVp output is by use of a high-voltage divider network. The equipment is bulky and must be connected between the high-voltage transformer and the x-ray tube. It is generally only used by service personnel or when a more extensive analysis of the voltage and current waveforms in the x-ray circuit is desired. One commercially available unit will provide direct readouts of kVp, mA, exposure time, mAs, mR/mAs, input line voltage, and current in the filament circuit.

mAs Linearity

The quantity of radiation delivered by an x-ray exposure is a direct function of the tube current (mA) and the exposure time. There is no *simple* way to measure the mA (although the high-voltage divider unit just mentioned, which must be physically connected into the x-ray circuit, will provide a direct readout of the mA). If the accuracy of the mA is in question, the x-ray service people should be able to determine it.

An *indirect* method of obtaining information about the relative accuracy of various mA stations is by checking the mAs linearity. Using an ionization chamber, measure the exposure at different mA stations keeping the time, kVp, distance, and collimation constant. The total exposure at each mA station should be in exactly the same proportion as the mA settings.

Beam Filtration

The amount of filtration in an x-ray beam will dramatically affect the radiation dose to the patient from an examination, particularly the entrance dose. Consequently the National Council on Radiation Protection and Measurements, the International Commission on Radiological Protection, and the Bureau of Radiological Health all have regulations regarding the total filtration required in the beam(5,6,7). A quick check of the adequacy of filtration can be made by checking the half-value layer (HVL, see Chap. 1) of the beam. At 80 kVp the HVL should be at least 2.37 mm of aluminum. To evaluate the HVL, position an ionization chamber in the middle of the beam at 24 to 30 inches from the focal spot. At 80 kVp select an mAs that provides almost a full-scale reading on the chamber and make an exposure. After inserting a sheet of 2.00-2.35 mm thick high-purity aluminum (series 1100) about midway between the focal spot and the chamber, make an identical exposure. If the second exposure is equal to or *greater* than one-half of the first exposure, the amount of filtration is adequate.

Total Output

Once a particular unit is calibrated, a rough but very quick check can be performed frequently to monitor for any unexpected output changes. Such a test may consist of making an exposure measurement at a specific kVp, mAs, and distance. These check readings should be reproducible to within 10% of the value empirically determined when a baseline value was first established for that unit. If the value lies outside of this range, or if a major change in the equipment has taken place, such as the installation of a new x-ray tube, a complete recalibration of the system should be performed. If this monitoring check is conducted in a consistent manner, the exposure per mAs should be reasonably consistent from machine to machine. At 80 kVp and 24 inches from the focal spot to the detector, single phase full-wave rectified machines

should read within 30% of 14 mR/mAs and three phase machines should read within 20% of 19 mR/mAs(8).

Congruence of the Light and X-ray Fields

Most x-ray collimation systems project a light field that is used to visualize the size and location of the x-ray field. The importance of collimation was emphasized in Chapter 3. However, close accurate collimation cannot be practiced unless the light field is congruent with the x-ray field. Shifts in the light field location are caused by shifts in the location of the light bulb filament, shifts in the position of the mirror, or shifts of the collimator housing on the tube head.

To perform the test, center a loaded 14 × 17-inch cassette on the table top at a source-image receptor distance (SID) of 40 inches. Select a field size of approximately 12 × 15 inches and position wires or strips of metal at the edges of the field and also at the centering cross hairs. A penny is traditionally used as a marker alongside the upper right-hand quadrant of the light field to indicate the orientation of the light field on the film. On the processed radiograph, the edge of the radiation field should correspond with the light field to within ±2% of the SID(9).

Some examinations, such as PA chests, require accurate centering in order to fit a large patient onto the film. Even minor light/x-ray field misalignment may cause cutoff of areas of interest and thus may require a retake examination. Also the larger SID's used in chest examinations require more critical light/x-ray field alignment. Therefore, for a chest unit, the test should be done at the chest SID rather than at 40 inches.

SID Indicator

All x-ray units that can be used at different distances must have a distance indicator. The use of the incorrect SID will result in an under- or overexposed film because of the intensity change based on the inverse square law. A method for determining the SID using a two-pinhole plate was discussed in Chapter 7. The indicator should be accurate to within 2% of the SID (or about 3/4" at a 40-inch SID). If a unit has several distance indicators, such as a measuring tape and wall markings or detents, they should all agree and be within the specified limits.

Focal Spot Size

The focal spot size is the source of penumbra (or geometrical unsharpness) and should be a prime consideration in deciding whether special techniques should be used in specific rooms (such as magnification and/or nonscreen techniques). There are two methods of determining focal spot sizes that are commonly employed: the pinhole camera method, which is the standard established by the National Electrical Manu-

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GROUP	FOCAL SPOT SIZE (NOMINAL)
1.(0.6 lp/mm)	2.0 (or smaller)
2.(0.7 lp/mm)	2.0 (or smaller)
3.(0.85 lp/mm)	2.0 (or smaller)
4.(1.0 lp/mm)	2.0 (or smaller)
5.(1.15 lp/mm)	1.8 (or smaller)
6.(1.4 lp/mm)	1.5 (or smaller)
7.(1.7 lp/mm)	1.3 (or smaller)
8.(2.0 lp/mm)	1.0 (or smaller)
9.(2.5 lp/mm)	0.8 (or smaller)
10.(2.8 lp/mm)	0.6 (or smaller)
11.(3.35 lp/mm)	0.5 (or smaller)

NOTE: It is important that the test be done consistently at the *same* kVp and mA stations since the focal spot size "blooms" as these factors are increased.

EVALUATION OF THE GENERAL CONDITION OF THE FACILITY

In addition to the specific tests listed, the general condition of the x-ray room should be evaluated. The following list was compiled by the Task Force on Quality Assurance Protocol of the Diagnostic Radiology Committee of the American Association of Physicists in Medicine.

1. *Mechanical integrity. A general observation of the diagnostic system should be made. Key items to look for are the presence of loose or absent hardware that may have been improperly installed or worked loose due to use. The functioning of meters, dials, pilot lights, and other indicators should be checked.*
2. *Mechanical stability. To obtain a diagnostic quality radiograph it is important to minimize relative patient motion. Of key importance from the equipment side are the stability of the x-ray tube hanger and the stability of the image receptor (i.e., table Bucky or wall-mounted cassette holder). The availability and adequacy of patient support devices such as the table or immobilizing devices should also be checked. In addition, it is important to check the reproducibility of positioning of the source and image receptor that may be indicated or controlled by physical marks or detents. Checks of the accuracy of angulation and position scales should be made.*
3. *As part of the check of structural stability, an inspection of the position locks on the machine should be carried out.*
4. *The external condition of the high voltage cables should be observed. Check to make sure that the retaining rings at the termination points are tight and that there are no breaks in the insulation or shielding. It is important to observe the draping of the cables. If they do not hang properly they can interfere with positioning of the tube, and if severely bent may lead to early cable failure.*
5. *The electrical safety of the system should be checked. Key areas include power cords, the wires to the exposure hand switch, multiple wire cables to the table and tube head, and the proper grounding of all components.*
6. *Source to image-receptor distance (SID) indicators should be checked. The consistency between multiple SID indicators (indicators on the tube support and the collimator) should be verified. The accuracy of these indicators should also be verified.*
7. *Verification of proper grid installation should be made. This check should also include a verification of the alignment of the x-ray source and the center of the grid*(12).

SUMMARY

The implementation of an x-ray quality assurance program should reduce the variability of x-ray output between the different machines in a department. It should also detect minor problems as they occur, before they become major. The combination of a processor quality assurance program with an x-ray quality assurance program should result in minimizing the retake rate of a radiology department. The benefits of such programs are twofold: a significant reduction in operating costs *and* a significant reduction in unnecessary patient exposure.

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LABORATORY EXERCISE 8

X-RAY QUALITY ASSURANCE

The goal of an x-ray quality assurance program is to ensure the consistent production of high-quality radiographs by eliminating the variability that may be introduced by the x-ray generating equipment. This variability may be the result of the improper or inconsistent functioning of any one x-ray machine, or may reflect variations in functioning from one machine to another. This exercise investigates the variability of x-ray output that may exist among radiographic rooms within an x-ray department.

Equipment

This exercise is to be conducted in the Diagnostic Radiology Department and requires the following apparatus:

Radiographic film
Aluminum stepwedge
Radiographic knee phantom
Cassette with par speed screens

Procedure

1. Make a set of radiographs, exposing one film in each of several (or in all) of the x-ray rooms in the diagnostic radiology department, using the *same* exposure conditions, the *same* object, the *same* cassette, and film from the *same* box. Use lead numbers to identify the different radiographic rooms. Save the films in a lighttight box and process them through the *same* processor at one time. Make the various exposures as quickly as possible so that the time between exposure and processing does not vary greatly between various radiographs.

Exposure parameters:
Object — knee phantom and aluminum stepwedge, placed side-by-side
kVp — 60
mAs — 40
Distance — 40 inches
Cassette — 10 × 12 inch, par speed screens
Collimation — to the cassette size

Examine the films for variations in image quality, contrast, and overall density.

2. Using the same procedure as in part 1, but utilizing only one radiographic room, make a series of exposures all at 40 mAs, but using the different mA stations available with appropriate changes in the exposure time.

Again examine the films for variations in image quality, contrast, and overall density.

QUESTIONS

1. From an examination of the radiographs obtained, does it appear that an x-ray quality assurance program has been implemented in this particular diagnostic radiology department? If not, is one needed? If so, is it successful?
2. How would you account for the variations, if any, noted in part 1?

9

REDUCTION OF UNNECESSARY PATIENT EXPOSURE

The U.S. Public Health Service estimated that 65% of the U.S. population was x-rayed for medical and dental purposes in 1970(1). The public is gaining an increased awareness of the possible consequences of radiation exposure and expects that all reasonable steps be taken to minimize that exposure. Although the risk to any individual patient is extremely small, the total amount of radiation delivered to the population will produce both somatic and genetic effects in that population related to the total dose delivered. For this reason, it is clear that every possible effort should be taken to obtain the necessary radiological information with the minimum possible radiation dose.

The previous chapters have dealt with the basic physical principles involved in radiology: the production of the beam, the interaction of the beam with the subject, and the production of the image from the remaining beam emergent from the subject. Throughout these chapters the effect of the various physical factors on the quality of the radiographic image has been stressed. Along with this concern for image quality the effect of each parameter on patient dose has been investigated. This chapter is oriented entirely to the reduction of patient exposure and will systematically discuss the decisions involved in producing a radiograph and how those decisions affect patient exposure. Although the primary concern of this syllabus is the physics of diagnostic radiology, this particular topic will necessarily delve into *all* aspects of the radiological examination.

A radiological examination can be thought of as consisting of three distinct processes: selection of the patient for an x-ray examination, performance of the examination, and interpretation of the radiological findings. Decisions made during each of these processes affect the radiation exposure of the patient. It has been estimated that at least 30% of present radiation exposure could be eliminated by proper utilization of each of these three processes. The conduct and interpretation processes are the traditional domain of radiology; in the past the radiologist's involvement in the selection process has been minimal.

SELECTION OF THE PATIENT

The radiologist is traditionally a consultant to the primary physician, providing additional clinical information by the use of radiology. It has been suggested that because of the biological risks involved, and to fully utilize his expertise for the benefit of all, the radiologist should assume a more active role in helping to determine the appropriate examinations rather than simply performing every examination requested without review. However, the selection of examinations purely from a radiation-reduction standpoint is inappropriate. The physician has a responsibility to the patient that cannot be slighted in favor of some indeterminate detriment to the population genetic pool. The need for diagnostic information cannot be weighed against a quantitatively ill-defined radiological risk to the future well-being of the patient. Substantial progress in the reduction of patient exposure must begin with the elimination of *unproductive* x-ray examinations. Understanding certain important selection criteria can aid the physician in deciding when an x-ray examination is warranted.

In general, four factors should be considered in the selection of symptomatic patients for x-ray examinations:

First, the examination should be relative to the symptoms. Will a particular examination yield the diagnostic information desired? Ordinarily, radiological studies are better utilized to confirm or disprove a tentative diagnosis than to formulate one. They can also provide additional information otherwise unobtainable regarding a known condition.

Second, whenever possible, there should be a reasonable expectation that the results of the radiological examination will significantly affect the care of the patient. If a patient's therapy will be unaltered by the results of a radiological evaluation, should it be performed? Unfortunately, nonmedical factors have crept into this judgment process. The possibility of litigation provides pressure for the use of otherwise unwarranted x-ray examinations. Also, patient anxiety is sometimes alleviated or expectations fulfilled by radiological

examination, even when other justification for the examination is somewhat tenuous. Therefore the motives for use of an x-ray examination must be evaluated.

Third, abdominal examinations of female patients are of particular concern whenever there is a possibility of irradiating an embryo or fetus. Animal studies involving relatively large doses of radiation (well above diagnostic levels) have shown that the immature, undifferentiated, and rapidly dividing cells comprising embryonic and fetal tissues are highly sensitive to radiation. The specific type of fetal radiation damage incurred is related to the dose and to the stage of pregnancy during which the irradiation takes place. The earliest stages of pregnancy, the first week or two in terms of the human gestation period, are most radiosensitive, with the predominant radiation effect being embryonic death. This is particularly significant in terms of practical radiation protection, since pregnancy may well be unsuspected during these first weeks (the preimplantation period). After implantation, the principle radiation effect is developmental damage, with the second through the sixth or seventh weeks of pregnancy (the period of organogenesis) being the critical period for the production of abnormalities(2).

It must be emphasized that there is no direct biological evidence that fetal radiation damage will occur as a result of the dose from any diagnostic x-ray procedure. In addition, all of the abnormalities attributed to radiation also occur naturally, i.e., without x-ray exposure (the natural incidence of observable birth defects is 4 per 100). However, some epidemiological studies suggest that exposure to diagnostic x rays in utero may statistically increase the *risk* of undesirable effects. As a result, the American College of Radiology and the American College of Obstetricians and Gynecologists have issued policy statements regarding the radiation exposure of fertile women(3,4), and the Bureau of Radiological Health has provided a technical overview of clinical methods of avoiding medical x-ray exposure of the human embryo and fetus(5). Federal guidelines for the radiation exposure of women have also been developed(6).

Examinations of women *known* to be pregnant present the possibility of direct irradiation of the fetus. Whenever possible, careful collimation and shielding should be used to exclude the fetus from the primary beam. If the fetus cannot be excluded without interfering with the view, consideration should be given to carefully limiting the study to a minimum number of films.

Fourth, the particular type of radiological examination to be performed must be considered with several points in mind. The age and health state of the patient should be weighed in deciding the extent of the examination. It may be possible to do a limited or a single study and then reevaluate, and possibly eliminate, the need for an extensive examination in some cases. Simultaneous studies, such as those of the gall bladder, kidneys, and stomach, should not be performed before careful evaluation of the patient's complaints and history.

X-ray examination of children should be carefully utilized, keeping in mind the special need to maintain childhood exposure to a minimum. The need for periodic examinations of children, such as those with congenital hip abnormalities, should be stringently reviewed — there should be no automatism in the process. When an examination is indicated, gonad shielding and tight beam restriction should be used in the conduct of the examination.

Fluoroscopic examinations should only be performed after careful consideration of alternatives. Fluoroscopic examinations expose the patient to much higher amounts of radiation than radiographic examinations because the fluoroscope operates for extended time periods as opposed to a fraction of a second for radiographs. In addition, fluoroscopic image quality is poor compared to radiography, and unless recorded on video tape or cine film, the image is not permanent. Therefore, fluoroscopy should only be used to study dynamic processes, and should not be used as a substitute for radiography.

The selection process is analyzed and discussed in detail in *The Selection of Patients for X-ray Examinations* (7).

CONDUCT OF THE EXAMINATION

After it has been decided that an x-ray examination is justified, the manner in which that examination is conducted will determine the patient's radiation exposure. It will also influence whether a correct diagnosis can be made and whether additional x-ray procedures need be done. Therefore, significant reduction of unnecessary patient exposure, as well as improvement in radiographic image quality, can occur during this phase of the radiological sequence.

Surveys of the radiation exposure delivered to a standard-sized patient reveal an extremely wide distribution of values, depending on the particular way the examination was conducted. Figure 9-1, from the Nationwide Evaluation of X-ray Trends (NEXT) program, is a graph of the radiation exposures delivered by an abdominal KUB scout film at various facilities throughout the United States(8). Since this data is for the same examination performed on the same size patient, it clearly demonstrates the dramatic effect that variations in the performance of an examination can have on the patient dose. Note that there are exposures as great as four times the median exposure for this particular examination.

The conduct of an x-ray examination can be separated into three distinct processes: choice of the equipment, operation of that equipment, and processing of the image.

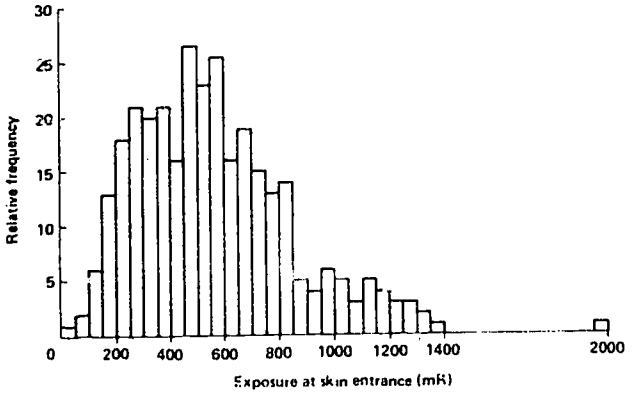

Figure 9-1. Frequency distribution of abdomen exposures(6).

Choice of Equipment

The choice of a particular machine for an examination is the responsibility of the radiologist. Routine examinations can be done on several types of general purpose machines, while special procedures generally require the use of specialized equipment. However, regardless of type, all x-ray equipment must possess certain features, namely a beam limiting device (collimator, cones, or diaphragms) and at least the minimum recommended amount of filtration.

Operation of the Equipment

This phase of the examination includes positioning of the patient, adjustment of the beam, selection of appropriate ancillary equipment (such as the proper film, intensifying screens, grid, shielding, etc.), and selection of appropriate machine technique factors (kVp and mAs). Most of these factors were discussed in detail and evaluated radiographically in previous chapters. Therefore, in this chapter, estimates of relative exposure values for the alternate choices will be made and comments on the advantages and disadvantages of the choices will be discussed.

Positioning of the Patient

Positioning the patient in a particular way and with proper patient instruction insures that the film will show the required view. In a good radiograph, the lesion or region of interest should be clearly visible and centered in the field. For example, lungs in expiration and scapulae in the lung fields are illustrative of improper positioning in a PA chest exam. If a retake is required because of improper positioning, the patient exposure is increased by 100%.

Adjustment of the Beam

Adjustment of the beam involves movement of the tube head to the proper distance and angle, limitation of the beam area, and filtration of the beam. As the *distance* from the tube to the film is decreased, the images of anatomical parts farther from the film become magnified, and patient exposure is increased. An error in the SID of only 5% (using 38 inches instead of 40 inches) will cause an increase in skin exposure of between 12% and 18%.

Beam limitation, best accomplished by variable rectangular collimators, is exceedingly important for several reasons. First, the patient's total exposure can be strikingly reduced with even small reductions in beam area, since less tissue volume is irradiated. Second, reduced beam area also causes a reduction in scattered radiation, since there is less tissue interacting with the beam. Finally, proper collimation may reduce the primary beam (and scattered "beam") exposure of the patient's critical or sensitive organs, such as the gonads, the thyroid, and the bone marrow. Because of these benefits, the x-ray beam should not be larger than the film used, and in many cases can be made smaller than the film, when the anatomical part to be examined is small. It is difficult to attach numbers to these errors because of the size and shape of the specific region and the location of any critical organs. If the area of the beam were twice as large as necessary (e.g., an 11 × 14" field instead of an 8 × 10" field) the dose integrated over the total volume of irradiated tissue would be doubled (assuming the patient thickness is constant). However, if a critical organ were included in the larger field, but not in the smaller, the critical organ dose could be increased by a factor of 100 or more.

In 1964 it was estimated that only 21% of all radiographs were made using a beam area smaller than the film area; by 1970 this figure had increased to 41%, a substantial improvement(1). However, it is obvious that a more concerted effort must be made to limit the beam area to the film area in radiological practice if significant progress is to be made in reducing unnecessary patient exposure.

Filtration of the beam, usually accomplished by adding additional sheets of aluminum in front of the tube port, is necessary to remove the very low energy photons which do not have sufficient energy to penetrate the patient and therefore do not contribute to the formation of the image. The recommended amount of filtering material (and thus the amount of low energy x-ray filtration that occurs) depends on the peak kilovoltage at which the x-ray machine is operated. Most diagnostic x-ray machines are required to operate with a total of 2.5 mm or more of aluminum equivalent filtration (taking into account the inherent filtration of the tube).

On those x-ray machines where the amount of filtration can be easily changed, a check for the proper amount of

filtration should be a part of the routine for every examination on that machine. If the filtration is inadvertently omitted, the skin exposure may be increased by a factor of 3 to 5 with a standard x-ray tube and as much as 30 to 100 with a beryllium window x-ray tube.

Selection of Ancillary Equipment

The proper selection and positioning of ancillary equipment is another important aspect of the conduct of the examination. In those views where the patient's gonads will be exposed to the primary beam in spite of tight collimation, such as might occur in examinations of the hip or lower spine, *gonad shielding* is advisable, unless the shield obscures the image of the area being examined(9). The male gonads are relatively easy to shield with devices such as a scrotal cup. Significant genetic dose reductions from the unprotected situation can be achieved since there is very little overlying tissue to protect the testes from the primary beam if they are exposed. The design and placement of gonad shields on females is more difficult due to uncertainty as to the location of the ovaries. In addition, because the ovaries are located near many organs of interest, shielding may interfere with the examination. However, some practitioners use wide bands of lead on the sides of the abdominal area in those examinations in which this shielding will not interfere with the visualization of the clinical area of interest. Fortunately, even if the ovaries cannot be avoided by collimation, the overlying tissues do reduce the dose to the ovaries from the primary beam.

Gonad shielding should not be used as a substitute for proper collimation, but rather as a supplement to collimation when the gonads must unavoidably lie in the direct beam. The proper shielding of the gonads when possible can reduce the gonad dose by 50 to 95%.

A significant factor affecting patient exposure is the choice of the *film imaging system*. Almost all radiographs are now made using film-intensifying screen combinations, which require only 1/3 to 1/300 of the nonscreen exposures. Screens are made with four different speed ranges, the slowest screen requiring over 30 times the exposure of the fastest. The speed of a film-screen combination is only achieved with some loss in the possible detail resolution of the system. However, since other factors enter into the maximum resolution of the radiographic system, notably penumbra, the adequacy of detail must be evaluated under actual conditions of use rather than on the basis of resolving power of the screens alone.

Most radiographic film is screen film, designed specifically to be used with intensifying screens. Since screen film is available with slightly different speeds and contrast, the most appropriate film in any installation should be determined by use. Film specifically designed for nonscreen techniques is also available. This film has a greater response to x-ray photons than screen film. Unfortunately, since nonscreen films generally cannot be used in 90-second processors and the volume of use is too small to retain much backlog, screen film is usually used for nonscreen applications. The substitution requires an increase in exposure of approximately 100%. The relative exposure levels (directly proportional to patient dose) of screen and nonscreen imaging systems is summarized in Table 9-1.

Table 9-1. RELATIVE EXPOSURE LEVELS OF SCREEN AND NONSCREEN IMAGING SYSTEMS (BASED ON MEDIUM SPEED SCREENS)

TYPE OF IMAGING SYSTEM	RELATIVE EXPOSURE LEVELS
Direct exposure (screen film)	20 - 40
Direct exposure (nonscreen film)	10 - 20
Detail screens	4
Medium speed screens	1
High speed screens	1/2
Very high speed screens	1/3
Rare earth screens	1/8 - 1/2

A significant problem in many x-ray examinations is the presence of a large amount of scattered radiation which "fogs" the film, decreasing the overall contrast. The relative amount of scattered radiation compared to primary radiation increases with both the thickness of the part and the area of the x-ray field. The three methods of decreasing the amount of scatter are collimation, the use of radiographic grids, and the air gap technique. The effectiveness of collimation in reducing scatter is limited by the necessary field size; to produce an acceptable film of a thick body part, the field would have to be too small for most examinations. (However, the field should be kept as small as possible even if other methods of scatter removal are used.) The air gap technique must be performed at large SID's to minimize both the magnification (increasing magnification reduces resolution) and the patient dose (since the patient is at a shorter SID than the film), and is generally used only for chest radiography. The most effective method of removing scattered radiation is by the use of *radiographic grids*. As was discussed in Chapter 3 and shown in Table 3-1, the problem with grids is that they require significant increases in exposure levels because of the absorption of primary radiation in the grid.

Although the grid technique causes an increase in patient exposure over nongrid techniques, the diagnostic value of the film can be considerably increased, possibly lessening the likelihood of retakes. However, because of the increased exposure required, grids should only be used when the amount of scatter is significant — that is, when thick, heavy parts are being radiographed. The

lowest grid ratio that gives acceptable results should be used. As shown in Figure 9-2, the increase in effectiveness of scatter removal decreases as the grid ratio increases. General guidelines for grid usage are available (see Chap. 3), but the ultimate decisions will have to be made under conditions of use.

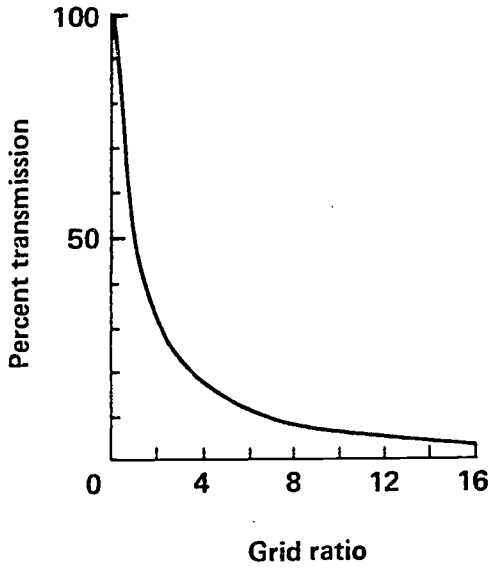

Figure 9-2. Percentage transmission of scattered photons through radiographic grids.

A common problem that reduces the diagnostic information of a radiograph is blurring due to motion. Various *immobilization devices* are available and should be used routinely in all cases where motion may be a problem. In those cases where immobilization is not possible, the exposure time can be decreased by increasing the tube current (if possible) or by using a faster intensifying screen. Failure to take appropriate action to solve the motion problem, especially in those patients too young or too incapacitated to follow instructions, may result in unnecessary retakes.

The *machine technique factors* (the kilovoltage, milliamperage, and exposure time) must be carefully selected to provide the x-ray penetration, film exposure, and film contrast appropriate for the examination. These factors will vary depending upon the speed of the film-screen combination used, the presence or absence of a grid, the mass of the patient part to be x-rayed, the source-image receptor distance, the amount of contrast desired and other factors. Operators of x-ray equipment ordinarily should refer to the departmental technique charts to select these exposure factors, rather than relying on memory.

Kilovoltage, designated in units of kVp, is of particular interest, because the operator may have wide latitude in kVp selection to produce adequate x-ray penetration of the part to be examined. When kVp is increased, the patient dose will be decreased, but the contrast will also be decreased. The magnitude of these changes depends upon the particular kVp, and the thickness and composition of the patient. However, an increase of 10 kVp can decrease the skin exposure by 5% to 30%.

Processing of the Image

A well-executed radiograph is useless if the diagnostic information is destroyed by poor processing techniques. This portion of the radiological examination is often overlooked in considerations of radiation reduction, even though poor processing can easily lead to an unnecessary second exposure of the patient (a 100% increase in patient exposure!). Difficulties in film processing fall into two general categories: improper developing techniques and film artifacts. Variations in the developer temperature, development time, or in the concentration or age of processing chemicals can result in underdeveloped or low contrast films, which could subsequently lead to increased patient exposures if the exposure techniques were adjusted to compensate for the light films rather than discovering and resolving the true cause of the light films. Film artifacts may obscure diagnostic information and in some cases could lead to an incorrect diagnosis, or they may lead to an unnecessary retake.

A well-established, faithfully maintained processor quality assurance program will essentially eliminate processor-related radiographic variability and processor-caused retakes, and will therefore play an important role in minimizing unnecessary patient exposure.

INTERPRETATION OF THE RADIOLOGICAL INFORMATION

The interpretation of the radiological findings is the purpose of the radiological process. Any influence that the radiological examination has on the management of the patient is a direct result of the interpretation of the radiograph. Regardless of the best intentions, no exposure-reduction activities in previous parts of the process should be allowed to hamper the acquisition of *needed* clinical information from the radiograph. However, the interpreter of the radiograph is in a position to positively influence the justifiable exposure-reduction opportunities in the previous phases of the process. The radiograph contains much information regarding the conduct of the examination. For example, x-ray machine position, patient position, collimation and shielding, film handling and processing, all leave radiographic evidence as to their adequacy. Critical evaluation and appropriate feedback to all of the personnel involved in the conduct process is necessary to improve their techniques. There are other factors that leave only subtle variations in the radiograph, variations which could easily be overlooked

when a direct comparison of films is not made, but which may cause large variations in patient exposure. Such variations can be caused by changes in kVp, filtration, type of film, speed of screens, grid ratios, time and temperature of processing, etc. Therefore it should be clear that radiology cannot be wholly practiced from the remoteness of the viewing room, but that an active involvement in the establishment and continuing reevaluation of all radiographic procedures is necessary to the practice of high quality radiology.

An equally important function of the interpreter (or interpreters as a group) is the evaluation of the productivity or efficacy of various radiologic examinations. The prescription of a particular examination for a patient presenting certain symptoms can be questioned or encouraged, based on the interpreter's experienced opinion about the radiological evidence likely to be discovered. The need or lack of need for further study, alternative diagnostic modes that might uncover additional information, and variations in future examination prescriptions for this patient or similar patients are examples of important feedback information from the interpreter to the referring physician. Such information could well reduce unnecessary population exposure by eliminating unproductive examinations in the earlier selection phase of the radiological sequence.

ESTIMATES OF PATIENT RADIATION DOSE

The question "What is the patient dose from a specific examination?" is one that is very difficult to answer. There are a number of different doses that can be determined which are valuable for different purposes, all of which may not be applicable in specific cases. The determination of a specific radiation dose is pointless without some knowledge of the biological significance of such an exposure. Generally speaking, radiation exposure can result in the production of damage in the individual irradiated (somatic effects) and/or can result in the production of undesirable effects in future generations of that individual (genetic effects). Various doses that can be determined and the biological effects to which they are most closely related are:

1. Bone marrow dose — leukemia induction
2. Thyroid dose — induction of thyroid carcinoma
3. Lens of eye dose — cataract formation
4. Gonad dose — genetic effects
5. Skin dose — general indicator of doses to nearby organs
   a. Entrance dose — high, large variability depending on kVp, filtration, distance
   b. Exit dose — low, approximately constant for all examinations using the same imaging system, since the films are all of approximately the same average density.

Comparison of any of these doses from one specific radiological examination to another may be meaningless and misleading. Ideally only a specific anatomical area of interest is exposed to the x-ray beam to obtain a radiograph; the remainder of the body is excluded from primary radiation exposure by beam restriction (therefore affecting the portion of the body subject to significant scattered radiation as well). Also, in many cases radiation shielding may be employed to protect specific areas from the primary beam when they do lie within the radiation field. Finally, specific organs (such as the ovaries) will receive different doses depending on whether the examination was performed as an AP or a PA examination because of the natural shielding provided by overlying tissue. The end result of all of these observations is that the values of the five specific doses mentioned above can vary tremendously for the same examination on the same patient depending upon the exact parameters of exposure.

With these limitations in mind, there are several sources that can be used to obtain estimates of dose levels from different examinations:

1. The table reproduced in the Appendix was derived by phantom dosimetry using technique factors selected by the Atomic Bomb Casualty Commission for Japanese atomic bomb survivors(10). Since the Japanese people are on the average smaller than people in the United States, the reported doses are somewhat lower than would be expected in this country. Unfortunately, similar comprehensive tables of United States data based on phantom measurements have not been published.
2. The tables provided in the Bureau of Radiological Health publication *Organ Doses in Diagnostic Radiology*(11) and its more concise adaptation, Handbook of Selected Organ Doses for Projections Common in Diagnostic Radiology(12), were developed by mathematical computations rather than by dosimetry.

RADIATION PROTECTION OF RADIOLOGICAL PERSONNEL

Although this topic is primarily concerned with the exposure of the patient, some comments about the occupational exposure of radiological personnel are warranted. Although the exposure of radiological personnel does not contribute appreciably to the total population radiation dose because of the relatively small number of individuals involved, the problem is important on an individual level. Since a technologist may take thousands of radiographs per year, and a physician and other medical personnel may participate in tens to hundreds of hours of fluoroscopy per year, the employment of protective procedures is essential. Ordinarily, procedures that reduce patient exposure do likewise for

radiological personnel, although of course not to the same degree. For example, tight collimation to reduce patient primary beam exposure and scatter to the film also reduces scattered x rays in the radiological room, which might expose personnel in certain examinations.

In addition, there are specific precautions for personnel. Only essential personnel should be allowed in the x-ray room, and then only when they are properly shielded. Lead aprons should be worn during fluoroscopy and lead barriers should be available to the operator to stand behind during radiography; these will reduce potential exposure by orders of magnitude. Radiological personnel should not be used to hold patients being x-rayed; rather, restraining devices should be used as necessary.

Because of the energy of diagnostic x rays and because of the quality of modern x-ray equipment, diagnostic x radiation can be relatively easily controlled. With proper enforcement of well-established protective procedures, there should be little occasion for unnecessary exposure of radiological personnel.

SUMMARY

The radiological process is designed to provide otherwise unobtainable diagnostic information that will affect the treatment of a patient. Whether or not unnecessary exposure of the patient can be reduced depends upon the cooperative efforts of all physicians engaged in any of the three major phases of the process: physicians who request x-ray examinations for patients, those who conduct examinations themselves or supervise the conduct of examinations by technologists, and those who interpret radiological findings are all in unique positions to effect a significant reduction of unnecessary radiation to the population. Legal enforcement of x-ray machine quality standards and training of nonphysician operators are very important in this regard, but ultimately, the success or failure of significant exposure-reduction efforts is the responsibility of the physician.

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LABORATORY EXERCISE 9

REDUCTION OF UNNECESSARY PATIENT EXPOSURE

The radiation dose to the patient is highly dependent upon the specific technique used in the examination. Particular factors that affect the dose are kVp, filtration, collimation, the use of radiographic grids, speed of the film and intensifying screens, and the use of localized shielding. This exercise quantitatively investigates patient exposure and illustrates the effects of methods that can be used to keep the dose as low as possible.

Equipment

This exercise is to be conducted in a full-sized x-ray room, although with some modifications the small teaching x-ray machine can be used. The following equipment is required:

Radiographic room
-or-
Small teaching x-ray machine
Radiation-measuring instrumentation
Radiographic pelvis phantom
Male gonad shield

Procedure

Place the pelvis phantom on the radiographic table at an SID of 40 inches and position it as you would a normal AP pelvis. Place the ionization chamber on the phantom (see Figure 1).

Record the dose measurements as indicated in the tables:

Column (1) A normal AP pelvis is usually positioned so that the 17-inch dimension is across the patient. Make sure that the field includes the entire structure of the pelvis but just excludes the position of the testes.

Column (2) Measured in the middle of the field on the surface of the phantom.

Column (3) Measured under the phantom, but *not* entirely behind any bony structure.

Column (4) and (5) Measured at the approximate location of the testes, with and without the gonad shield (Figures 2 and 3).

Column (6) Collimate so that the position of the testes are 5 cm or more from the edge of the primary beam (do not use the gonad shield).

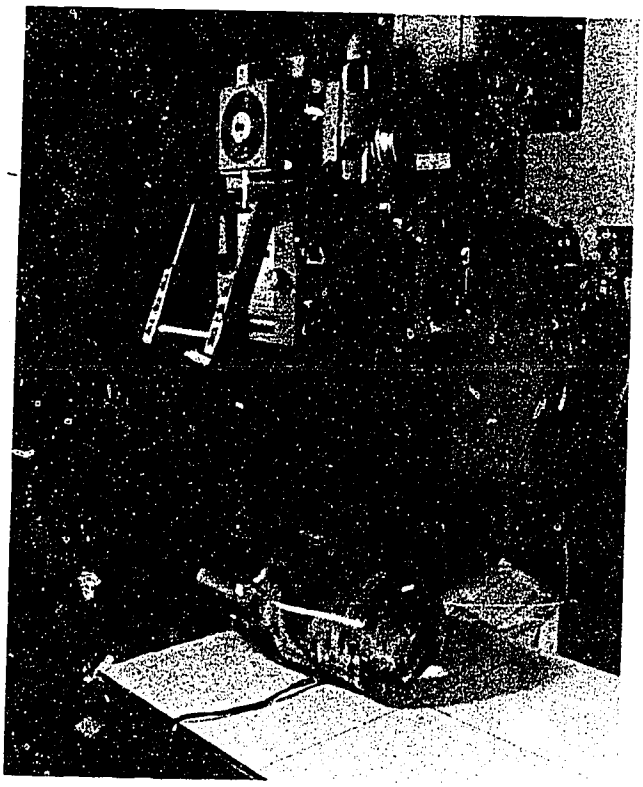

Figure 1. Experimental set-up with probe measuring exit dose.

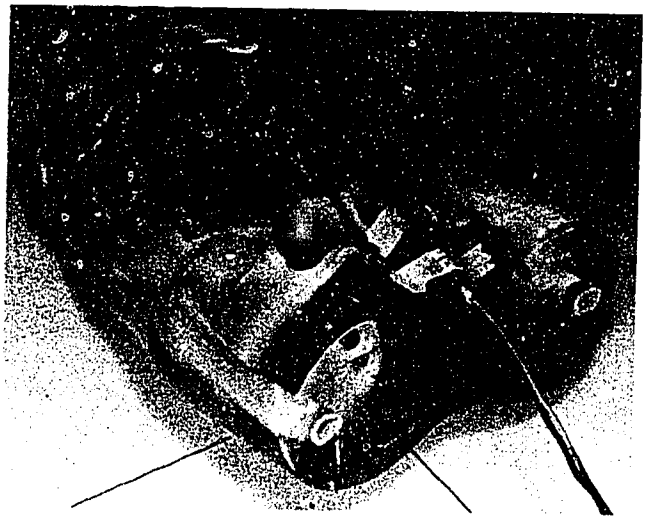

Figure 2. Probe measuring unshielded testes exposure.

Figure 3. Probe measuring shielded testes exposure.

1. *Effect of kVp*

The following techniques are for a 16:1 grid and a high speed calcium tungstate film-screen combination. These kVp's probably represent the extremes of high and low kVp technique used in practice for a pelvis examination. The mAs values should yield approximately equal exit dose values (and therefore films of approximately equal density).

			(1)	(2)	(3)	(4)	(5)	(6)
			FIELD	ENTRANCE	EXIT	TESTES DOSE		
kVp	mAs	FILTRATION	SIZE	DOSE	DOSE	NO SHIELD	SHIELDED	EXCLUDED
70	60	normal	14 × 17					
90	30	normal	14 × 17					

2. *Effect of Filtration*

Remove the normal filtration and compare the entrance and exit doses with the values obtained in part 1.

			(1)	(2)	(3)	
			FIELD	ENTRANCE	EXIT	
kVp	mAs	FILTRATION	SIZE	DOSE	DOSE	
70	60	inherent	14 × 17			
90	30	inherent	14 × 17			

3. *Effect of Field Size*

Replace the normal filtration and make the following measurements using the largest obtainable field size. Compare these values with those in part 1.

			(1)	(2)	(3)	(4)	(5)
			FIELD	ENTRANCE	EXIT	TESTES DOSE	
kVp	mAs	FILTRATION	SIZE	DOSE	DOSE	NO SHIELD	SHIELDED
70	60	normal	max.				
90	30	normal	max.				

DISCUSSION OF LABORATORY EXERCISES

LABORATORY EXERCISE 1

The output of an x-ray machine under the conditions of this exercise is:

1. Directly proportional to the tube current
2. Directly proportional to the exposure time
3. Approximately proportional to the 2.3 power of kilovoltage

The first two statements are essentially valid under all conditions, but the third varies with the total amount of filtration in the beam. With a lightly filtered beam, the output measured at the machine varies approximately as the square of kVp. After the beam has passed through a thick patient (which in effect filters the beam), the output measured on the exit side of the patient may vary as the third or fourth power of kVp.

As a result of this difficult-to-specify relationship between output and kVp, it is easier to vary output predictably by changing mA or time (mAs) rather than by changing kVp, because the former relationship (output vs. mAs) is theoretically exact. Of course, there are limitations to this approach also: there is a maximum mA possible on any machine, the time is limited by possible motion difficulties, the total mAs at any kVp is limited by heat loading, and mAs settings on machines are often in discrete steps rather than constantly variable.

The main point is that output variation by mAs is reasonably exact and predictable, while output variation by kVp is a complex matter. Another more important factor, which will be explored in the second exercise, is that the contrast of the image is affected dramatically by kVp variations, as is patient dose. Thus alterations in kVp to affect output also have "side effects."

The attenuation curves from part 4 of the exercise illustrate the importance of filtration. The exposure rate is decreased dramatically by the first few millimeters of aluminum, indicating that a large number of low energy photons are eliminated. Since a normal adult chest has a radiation transmission roughly equivalent to 1 inch of aluminum, it is obvious that little information could be produced by these low energy photons. As more filtration is added, the attenuation curve tends to approach a straight line (when plotted on semilogarithmic graph paper). This indicates that additional amounts of filtration do not alter the shape of the x-ray spectra very markedly. Once a reasonable "straight line" region has been achieved, additional filtration reduces patient entrance dose only slightly.

LABORATORY EXERCISE 2

The three images of the aluminum stepwedge made at different values of kVp (part 2) illustrate a large variation in contrast. The 110 kVp stepwedge shows "low" contrast, i.e., there are many fine gradations of gray. Therefore, low contrast and a "long gray scale" are synonyms. The 50 kVp stepwedge has "high" contrast: there are fewer gradations of gray and the differences between them are more abrupt. Consequently high contrast is synonymous with a "short gray scale" or "short scale contrast." Notice that the low contrast technique allows a greater range of x-ray exposures to be visualized. If you were interested in diagnostic information at both step 1 and step 10 of the stepwedge, a high kVp technique is necessary. Thus, a low contrast technique has greater "latitude," i.e., it allows a greater deviation in the exposure than does a high contrast technique.

The other stepwedge film made with four different amounts of filtration and a constant kVp (part 3) shows almost no change in contrast. Therefore, the addition of new high energy photons to the x-ray spectrum (increasing kVp) is far more important in affecting the radiographic image than eliminating low energy photons (by the addition of filtration). However, the patient skin dose is affected substantially by the addition of filtration since the low energy photons removed would reach the skin but have a small range and would not reach the film.

These concepts are further illustrated by the six lateral knee films of part 5. All six films would probably be accepted by most radiologists as "good" films, and if seen separately during a working day, would be considered to be essentially identical films. When viewed together, however, differences can be identified and some of the films can be labeled as "better" than others. The measurements of skin exposure reveal a variation of almost a factor of five. The total dose integrated over the entire volume of tissue which is irradiated will not vary as much as the skin dose because the exit doses are roughly equal (the film "darkness" is roughly equal in each case). The decision ultimately becomes, "What levels of kVp and filtration can I use routinely and still get the quality of films that I desire?"

The AP radiographs of the knee with and without paraffin blocks (roughly equivalent to soft tissue) illustrate the problem of scattered radiation. The overall darkening of the film due to scattered radiation "fog" decreases the contrast markedly. An overall exposure to the film affects

the lightest areas far more than the darkest areas because the additional radiation is a significant portion of the total radiation creating that part of the image. Therefore, the lightest areas are darkened considerably while the darkest areas are essentially unchanged visually. As a result, the total gray scale is reduced substantially.

LABORATORY EXERCISE 3

The films from part 1 dramatically illustrate the value of collimation in reducing scattered radiation. However, it is obvious that collimation cannot be used exclusively as a means of reducing scatter since the field size would have to be extremely small when radiographing a thick object such as a pelvis.

The four films made with the 3 inch diaphragm [no grid (from part 1a); and 6:1 linear, 12:1 linear, 6:1 crossed grids (from part 2a)] show successive improvements in image quality, with a corresponding increase in patient dose (directly proportional to 42, 270, 450, and 585 mAs). There is very little change between the 12:1 linear and 6:1 crossed grids. The 30% increase in patient dose for the 6:1 crossed grid certainly does not seem to be justified. Ideally every radiologist should have access to a complete set of grids and phantoms. He could then determine which grids provide the detail he deems necessary (in any examination), without using an unnecessarily high dose technique.

The film from part 2c illustrates two interesting points. First, a 12:1 grid does not allow much lateral positioning error, less than 1 inch. Secondly, the slight variations in density across any one strip indicate that the grid is not "perfect." The strips are not all aligned absolutely correctly, an essentially impossible task with roughly 80 strips of lead and 80 strips of interspace material in every inch!

The air gap technique can be used in some situations, but it is not practical under the constraints of this exercise. However, even under these circumstances, the air gap does provide an improvement in the film quality.

LABORATORY EXERCISE 4

The series of films from parts 1 and 2 illustrate the variation in resolution produced by different speed intensifying screens. Extremity films are usually done with cardboard exposure holders or with detail intensifying screens.

Since the detail visibility depends upon the contrast as well as the sharpness (as discussed in the introductory lecture) it is somewhat difficult to compare the cardboard and screen exposures (although the films from part 3 should make this easier). The only reasonable argument for using cardboard exposure holders rather than detail screens is the possibility of screen artifacts, which could mimic a foreign body. However, if the screens are cleaned regularly and handled properly, this should not be a significant problem.

Another major factor involved in sharpness is penumbra (discussed in Chap. 6). The focal spot size in the teaching x-ray machine is 0.5 × 0.5 mm and the penumbral effects are minimized (as compared to the normal clinical situation where 1.0 × 1.0 mm and 2.0 × 2.0 mm focal spots are generally used). If a larger focal spot were used, the difference between the slower speed screens would be reduced.

Ultimately, the final decision on which screen is appropriate will have to be made by the radiologist. There is a definite compromise between patient exposure and resolution; each radiologist will have to decide in his own mind what level of detail he must have under various circumstances, bearing in mind the resultant dose level associated with that level of detail.

LABORATORY EXERCISE 5

Any darkroom which will produce no fogging after 4 minutes of film exposure is in excellent safelight condition. If the 4-minute film shows fogging but the 2-minute film does not, the darkroom is in good condition. These comments are based on the fact that film should either be inside of the lighttight film bin or inside of the cassette and only exposed to safelights for short time periods for purposes of handling and insertion into the processors.

Most film manufacturers make from 2 to 5 grades of general radiographic film (in addition to special film such as cineradiographic or mammography film) but the differences may be quite subtle and of greater importance to the film salesman than the radiologist. Variations between the films of different manufacturers may be more significant. However, there are distinct differences between the green-sensitive films used for rare-earth intensifying screens as compared to the blue-sensitive films used for calcium tungstate intensifying screens. The films from part 4 illustrate these facts.

If the differences between two or three films under consideration are quite small, two other factors that should be considered are: Is there any variation in film response from sheet to sheet or batch to batch? Is there any problem in getting film supplies on short notice?

LABORATORY EXERCISE 6

The sensitometric variation between the x-ray processors in any given x-ray department will vary greatly depending on the operating conditions of those pro-

cessors and whether or not the department has an active, effective quality assurance program. Some departments deliberately set one or more processors to a lower contrast level than that which would be achieved by processor optimization or by operation in accordance with film and chemistry manufacturers' recommendations. This is undesirable for the following reasons:

1. Reduced contrast is achieved by overexposure and underdevelopment. This results in an unnecessary increase in patient dose.
2. If the processors are not sensitometrically matched then they cannot be used interchangeably; this becomes especially important when one processor is temporarily out of operation and its workload is shifted to the other processor(s).

LABORATORY EXERCISE 7

The magnification films taken in part 2a show four of the objects at approximately equal film densities and the fifth significantly lighter. The "lighter" object is the one deepest in the phantom and essentially on the surface of the cassette. Because of the proximity of this object to the film, scattered radiation cannot "fog" the image of that object.

The radiographs of the distortion phantom may illustrate a number of interesting factors depending upon the objects incorporated within it:

1. Circular images may be formed by:
   a. A sphere in the center of the beam (Fig. 7-6)
   b. A flat circular object placed parallel to the film plane
2. Egg-shaped images may be formed by:
   a. A sphere laterally positioned in the beam (Fig. 7-6)
   b. A flat circular object tilted with respect to the film plane (Fig. 7-5)
   c. A flat egg-shaped object parallel to the film plane
3. The orientation of a screw or similar long object may possibly be determined by a variation in magnification from one end to the other (Fig. 7-5).

Radiographic magnification (rather than photographic magnification) is only practical with very small focal spot sizes. The focal spot size of the teaching x-ray machine is 0.5 × 0.5 mm and the increase in penumbral effects is clearly evident in the magnified films (magnification approximately equal to 2). Conventional radiographs made with focal spots of 1.0 × 1.0 mm or 2.0 × 2.0 mm will show significantly less detail in the magnified images.

A magnification ring (or circle) is used because no matter what its orientation, one of its diameters will be visible (i.e., the largest dimension of the image of the ring will be the magnified image of the diameter of the ring).

LABORATORY EXERCISE 8

The improper or inconsistent mechanical functioning of an x-ray generator may be manifested in many ways. Some possible inadequacies include:

1. Incorrect timing
2. Nonlinear mA stations
3. Incorrect kVp
4. Inadequate filtration
5. Misaligned radiation and light fields
6. Inaccurate source-image receptor distance indicator
7. Increased focal spot size

X-ray generator quality assurance tests are generally conducted by trained x-ray service personnel, by physics staff, or in some instances (especially routine monitoring tests) by x-ray technologists; however, the radiologist should be aware of these tests and should familiarize himself with the manner in which they are conducted as well as the purpose of the tests.

LABORATORY EXERCISE 9

This exercise is basically a summary of all of the previous exercises, performed in a clinical environment. The following methods of ***decreasing*** patient dose were numerically evaluated:

1. Increasing kVp
2. Increasing filtration
3. Decreasing field size
4. Use of gonad shielding (gonad dose only)
5. Careful collimation to exclude the gonads from the primary beam

Some other factors that also lead to decreased patient dose but that were not evaluated are:

1. Use of faster film-screen combinations
2. Use of the lower ratio grids
3. Use of the air gap technique (where appropriate)
4. Proper processing methods

Good radiological practice has as its goal the consistent production of high-quality radiographs achieved with the lowest possible patient dose.

APPENDIX

TABLE I: DOSE FROM ROENTGENOGRAPHY AND FLUOROSCOPY, DEPARTMENT OF RADIOLOGY, ATOMIC BOMB CASUALTY COMMISSION

Site of Examination	Projection	Average Thickness (cm)	Film Size (inch)	kVp	mAs	Added Filtration (mmAl)	FFD (inch)	Bone Marrow Integral Dose (g-rad)	Gonadal Dose (mrad) Male	Female	Surface Dose (mrad)
Skull x+	PA	19	10 X 12	84	20	3.0	36	8.56	0.93 ○	0.11 ○	111
	Lateral	16	10 X 12	74	20	3.0	36	10.2	0.04 ○	0.05 ○	96.6
	Occipital	23	10 X 12	90	20	3.0	36	12.6	0.38 ○	0.32 ○	171
	Submentovertex	23	10 X 12	90	20	3.0	36	12.5	0.04 ○	0.13 ○	147
	AP*	19	10 X 12	84	20	3.0	36	5.7	0.93 ○	0.11 ○	110
Paranasal sinuses x	Caldwell, Waters	19	8 X 10	78	20	3.0	36	3.07	<0.01 ○	<0.01 ○	117
	Lateral	16	8 X 10	66	20	3.0	36	3.25	<0.01 ○	<0.01 ○	90.2
	Submentovertex	25	8 X 10	86	20	3.0	36	2.19	<0.01 ○	<0.01 ○	120
Mastoids x	PA	22	8 X 10	74	20	3.0	36	0.86	<0.01 ○	<0.01 ○	60.8
	Stenvers, Law's	16	8 X 10	78	20	3.0	36	1.27	<0.01 ○	<0.01 ○	65.7
	Occipital +	25	10 X 12	90	20	3.0	36	1.26	0.38 ○	0.32 ○	171
Mandible	PA*x+	19	10 X 12	84	20	3.0	36	3.1	<0.01 ○	<0.01 ○	120
	Oblique*	16	8 X 10	68	20	2.5	40	3.1	<0.01 ○	<0.01 ○	120
	Lateral*x+	16	10 X 12	70	20	3.0	36	1.3	<0.01 ○	<0.01 ○	66
Neck (soft tissue)	AP	13	8 X 10	100	5	2.5	72	0.34	<0.01 ○	<0.01 ○	7.94
	Lateral	13	8 X 10	100	5	2.5	72	0.39	<0.01 ○	<0.01 ○	6.92
Cervical spine	AP	13	8 X 10	90	20	2.5	40	2.87	0.02 ○	0.02 ○	98.1
	Lateral	13	8 X 10	92	40	2.5	72	1.40	<0.01 ○	<0.01 ○	34.6
	Oblique*	16	8 X 10	80	40	2.5	72	2.1	0.01 ○	0.01 ○	66
Thoracic spine	AP	20	11 X 14	100	30	2.5	40	18.2	0.19 ○	0.26 ○	249
	Lateral	30	11 X 14	110	60	2.5	40	55.3	0.17 ○	0.54 ○	707
	Oblique*	25	11 X 14	100	40	2.5	40	31	0.18 ○	0.35 ○	400
(small cone)	AP*	20	8 X 10	100	30		40	13	0.14 ○	0.19 ○	250
(small cone)	Lateral*	30	8 X 10	110	60		40	40	0.12 ○	0.39 ○	710
Lumbar spine	AP	17	11 X 14	100	30	2.5	40	25.7	14.7 ○	70.4 ●	221
	Lateral	27	11 X 14	120	60	2.5	40	57.2	9.77 ○	61.5 ●	820
(small cone)	Lateral*	27	8 X 10	120	70	2.5	40	39	5.7 ○	72 ●	820
	Oblique*	24	11 X 14	120	40	2.5	40	34	20 ○	94 ●	290
Lumbosacral spine	Lateral*	30	11 X 14	120	70	2.5	40	41	55 ○	82 ●	1100
Pelvis	AP	17	11 X 14	100	30	2.5	40	28.9	83.0 ●	79.0 ●	219
	Lateral*	30	11 X 14	120	70	2.5	40	64	55 ●	82 ●	1100
	Oblique*	22	11 X 14	100	40	2.5	40	47	110 ●	110 ●	660
Sacroiliac joint	Oblique*	22	11 X 14	100	40	2.5	40	39	110 ●	110 ●	660
Sacrum	AP*	19	10 X 12	100	30	2.5	40	26	83 ●	79 ●	220
	Lateral*	27	10 X 12	120	60	2.5	40	41	55 ●	82 ●	1100
Shoulder	AP	16	8 X 10	80	20	2.5	40	2.81	<0.01 ○	0.02 ○	68.9
Arm	AP, lateral	10	11 X 14/2	70	5	2.5	40	<1	<0.01 ○	<0.01 ○	—
Forearm	AP, lateral	8	10 X 12/2	66	5	2.5	40	<1	<0.01 ○	<0.01 ○	—
Hand, wrist	PA, oblique, lateral	4	10 X 12	54	5	2.5	40	<1	<0.01 ○	<0.01 ○	—

*From: Antoku, S. and Russell, W. J., Dose to the active bone marrow, gonads, and skin from roentgenography and fluoroscopy. *Radiology* 101:669-678, December 1971.

TABLE I: DOSE FROM ROENTGENOGRAPHY AND FLUOROSCOPY, DEPARTMENT OF RADIOLOGY, ATOMIC BOMB CASUALTY COMMISSION (*continued*)

Site of Examination	Projection	Average Thickness (cm)	Film Size (inch)	kVp	mAs	Added Filtration (mmAl)	FFD (inch)	Bone Marrow Integral Dose (r-rad)	Gonadal Dose (mrad) Male	Gonadal Dose (mrad) Female	Surface Dose (mrad)
Thigh	AP	17	14 X 17	100	20	2.5	40	20.4	108 (16.7) ●	60.0 ●	153
	Latéral	17	14 X 17	100	20	2.5	40	8.2	16.7 ●	13.9 ●	175
Leg (tibia, fibula)	AP, lateral	12	14 X 17	74	5	2.5	20	<1	<0.01 ○	<0.01 ○	—
Chest	PA	21	14 X 17	100	5	2.5	72	1.73	0.02 ○	0.04 ○	9.21
	Lateral	32	14 X 17	110	15	2.5	72	3.29	0.03 ○	0.08 ○	37
	Lordotic*	23	11 X 14	100	10	2.5	72	1.6	0.02 ○	0.02 ○	18
	Oblique*	27	14 X 17	100	10	2.5	72	2.3	0.02 ○	0.04 ○	17
	Bucky PA	20	14 X 17	100	40	2.5	72	14	0.16 ○	0.32 ○	74
	Bucky lateral	30	14 X 17	110	80	2.5	72	18	0.16 ○	0.43 ○	200
	Bucky oblique*	25	14 X 17	100	60	2.5	72	17	0.18 ○	0.40 ○	130
	AP	20	14 X 17	100	5	2.5	60	1.0	0.03 ○	0.05 ○	9.21
	Barium lateral	30	14 X 17	110	15	2.5	72	3.3	0.03 ○	0.08 ○	37
	Barium oblique*	25	14 X 17	100	10	2.5	72	2.3	0.02 ○	0.04 ○	17
	Stereoscopic*	20	14 X 17	100	5	2.5	72	1.7	0.02 ○	0.04 ○	9.2
	Decubitus*	20	14 X 17	100	5	2.5	72	1.7	0.02 ○	0.04 ○	9.2
Abdomen	AP	17	14 X 17	100	20	2.5	40	17.7	11.6 (6.59) ○	51.1 ●	159
	PA*	17	14 X 17	100	20	2.5	40	33	3.3 ○	16 ●	160
	Lateral*	27	14 X 17	120	60	2.5	40	57.2	9.77 ○	61.5 ●	820
	Oblique*	22	14 X 17	100	30	2.5	40	27	17 ○	77 ●	240
Rib	PA	20	14 X 17	100	5	2.5	72	1.73	0.02 ○	0.04 ○	9.21
	PA oblique	25	10 X 12	90	10	2.5	36	14.9	0.13 ○	0.37 ○	151
Chest	Fluoroscopy (conv)**			90		2.5		37.2/min	0.34/min ○	1.52/min ○	1270/min
	Fluoroscopy (image)**			90†		3.0		4.80/min	0.03/min ○	0.38/min ○	150/min
	Spot**	20	8 X 10	90	PHT	3.0		4.20	0.04 ○	0.08 ○	46
Bronchogram	Fluoroscopy (conv)*			90		2.5		30/min	0.30/min ○	1.4/min ○	1000/min
	Fluoroscopy (image)*			90†		3.0		3.9/min	0.03/min ○	0.35/min ○	120/min
	PA*	20	14 X 17	100	7	2.5	72	2.42	0.03 ○	0.06 ○	12.9
	Lateral*	30	14 X 17	110	15	2.5	72	3.29	0.03 ○	0.08 ○	37
	Oblique*	25	14 X 17	100	10	2.5	72	2.3	0.02 ○	0.04 ○	17
Pharynx	Fluoroscopy (conv)*			90		2.5		30/min	<0.01/min ○	<0.01/min ○	680/min
	Fluoroscopy (image)*			90†		3.0		5.3/min	<0.01/min ○	<0.01/min ○	110/min
	Spot*	20	8 X 10	90	PHT	3.0		<1	<0.01 ○	<0.01 ○	15
Barium swallow	Fluoroscopy (conv)*			90		2.5		30/min	0.30/min ○	1.4/min ○	1000/min
	Fluoroscopy (image)*			90†		3.0		3.9/min	0.03/min ○	0.35/min ○	120/min
	Spot*	20	8 X 10	90	PHT			4.2	0.04 ○	0.06 ○	46.0
Esophagram (4-way heart series)	PA*	20	14 X 17	100	5	2.5	72	1.7	0.02 ○	0.04 ○	9.2
	Lateral*	30	14 X 17	110	15	2.5	72	3.3	0.03 ○	0.08 ○	37
	Oblique*	25	14 X 17	100	8	2.5	72	1.84	0.02 ○	0.03 ○	13.6

TABLE I: DOSE FROM ROENTGENOGRAPHY AND FLUOROSCOPY, DEPARTMENT OF RADIOLOGY, ATOMIC BOMB CASUALTY COMMISSION (*continued*)

Site of Examination	Projection	Average Thickness (cm)	Film Size (inch)	kVp	mAs	Added Filtration (mmAl)	FFD (inch)	Bone Marrow Integral Dose (g-rad)	Gonadal Dose (mrad) Male	Gonadal Dose (mrad) Female	Surface Dose (mrad)
Upper gastrointestinal series	Fluoroscopy (conv)**	17		90		2.5		34.0/min	12.4/min ○	81.1/min ○	1220/min
	Fluoroscopy (image)**	17		90†		3.0		7.21/min	0.348/min ○	12.8/min ○	328/min
	Spot**	17	8 × 10	90	PHT	3.0		1.35	0.07 ○	2.68 ○	101
	AP (survey film)	17	14 × 17	100	20	2.5	40	17.7	11.6 (6.59) ○	51.1 ●	159
	PA	17	14 × 17	120	20	2.5	40	39.0	7.54 ○	33.1 ●	265
	RAO 45° } Flx.	22	11 × 14	120	30	2.5	40	46.5	3.20 ○	29.6 ●	400
	RAO 60°	26	11 × 14	120	40	2.5		34.7	3.65 ○	24.7 ●	413
Small-bowel series	Fluoroscopy (conv)*	17		90		2.5		73/min	37/min ○	320/min ●	1800/min
	Fluoroscopy (image)*	17		90†		3.0		19/min	5.7/min ○	77/min ●	400/min
	Spot*	17	8 × 10	90	PHT	3.0		7.3	15 ○	52 ●	440
	AP*	17	14 × 17	120	20	2.5	40	22	30 ○	68 ●	260
Gallbladder series	PA prone	17	14 × 17	120	20	2.5	40	41.4	11.0 ○	38.9 ●	223
	Prone oblique	22	8 × 10	120	30	2.5	40	28.8	5.59 ○	38 ○	322
	Erect oblique x	22	8 × 10	90	20	3.0	36	11.1	0.80 ○	5.69 ○	139
	Fluoroscopy (conv)*	17		90		2.5		20/min	0.2/min ○	1.8/min ○	1200/min
	Fluoroscopy (image)*	17		90†		3.0		6.7/min	0.1/min ○	0.6/min ○	400/min
	Spot*	17	8 × 10	90	PHT	3.0		11	1.0 ○	7.1 ○	173
Barium enema	AP (Survey film)	17	14 × 17	120	20	2.5	40	75.5	60.2 ○	132 ●	675
	Fluoroscopy (conv)**	17		90		2.5		112/min	62.0/min ○	562/min ○	2410/min
	Fluoroscopy (image)**	17		90†		3.0		30/min	11/min ○	140/min ○	480/min
	Spot**	17	8 × 10	90	PHT	3.0		5.90	3.20 ○	28.0 ○	110
Intravenous urogram	AP abdomen (KUB)	17	14 × 17	120	30	2.5	40	75.5	60.2 (17.9) ○	132 ●	675
	AP bladder	20	14 × 17	120	30	2.5	40	102	181 ●	105 ●	659
Intravenous cholangiogram	PA*	17	14 × 17	120	20	2.5	40	31	8.3 ○	29 ●	170
	Oblique*	22	11 × 14	120	30	2.5	40	47	12 ○	44 ●	250
Myelogram	Fluoroscopy (conv)*	17		90		2.5		54/min	25/min ○	200/min ○	1500/min
	Fluoroscopy (image)*	17		90†		3.0		13/min	3.0/min ○	45/min ○	360/min
	Spot*	17	8 × 10	90	PHT	3.0		28	16 ○	94 ○	820

TABLE I: DOSE FROM ROENTGENOGRAPHY AND FLUOROSCOPY, DEPARTMENT OF RADIOLOGY, ATOMIC BOMB CASUALTY COMMISSION (*continued*)

Site of Examination	Projection	Average Thickness (cm)	Film Size (inch)	kVp	mAs	Added Filtration (mm Al)	FFD (inch)	Bone Marrow Integral Dose (g-rad)	Gonadal Dose (mrad) Male	Female	Surface Dose (mrad)
Hysterosalpingogram	Stereoscopic*	17	10 X 12	120	30	2.5	40	31		73 ●	210
	Oblique*	22	10 X 12	120	30	2.5	40	31		110 ●	680
	Fluoroscopy (conv)*	17		90		2.5		110/min		560/min ●	2400/min
	Fluoroscopy (image)*	17		90†		3.0		30/min		140/min ●	480/min
	Spot*	17	8 X 10	90	PHT	3.0		19		61 ●	200
Skull tomogram	AP*	19	8 X 10	120	20	2.5	40	16	<0.01 ○	<0.01 ○	210
Pneumoencepnalogram	PA*	19	10 X 12	84	20	2.5	36	8.6	0.93 ○	0.11 ○	110
	Lateral*	16	10 X 12	70	26	2.5	36	10	0.04 ○	0.50 ○	97
Paranasal sinuses	Tomo PA*	19	8 X 10	120	20	2.5	40	16	<0.01 ○	<0.01 ○	210
	Tomo submentovertex*	25	8 X 10	120	20	2.5	40	16	<0.01 ○	<0.01 ○	210
Thoracic spine	Tomo AP*	20	8 X 10	110	20	2.5	40	18	0.17 ○	0.21 ○	190
	Tomo lateral*	30	8 X 10	80	150	2.5	40	24	0.07 ○	0.24 ○	310
Chest tomogram	AP	20	8 X 10	90	20	2.5	40	8.47	0.08 ○	0.10 ○	91.8
	Lateral*	30	8 X 10	120	20	2.5	40	16	0.12 ○	0.20 ○	370
Lumbar spine	Tomo AP*	17	8 X 10	80	150	2.5	40	54	31 ○	148 ●	470
Pelvis	Tomo*	17	8 X 10	120	20	2.5	40	21	85 ●	81 ●	220
Gallbladder	Tomo PA*	17	8 X 10	120	20	2.5	40	51	5.6 ○	38 ○	470
Intravenous urogram	Tomo*, kidneys	17	11 X 14	120	20	2.5	40	33	12 ○	80 ●	450

Routine projections per examination are underlined.
Collimators were used in all radiography, except with skull unit in which cones were used unless otherwise indicated.
x Skull unit.
+ No cone.
Conv. Conventional fluoroscopy.
Image Image-intensifier fluoroscopy.
PHT Phototimer.
†. kVp for fluoroscopy with image intensifier varied as automatic brightness control.
mA for fluoroscopy with image intensifier was 0.5 or 1.0.
mA for fluoroscopy with conventional unit was 3.0.
All doses were calculated by phantom dosimetry with ionization chambers in the phantom except:
*Dose from phantom dosimetry data of examinations with similar conditions and technical factors of exposure
**Dose calculated from surface dose obtained by film densitometry and ionization chambers.
Doses in parentheses indicate male gonads were shielded with lead apron.
Gonad locations with respect to the direct x-ray beam: ○ outside; ◐ inside during some of the exposures; ● inside.
Radiography x-ray beams were collimated to a field slightly larger than the film size. The mean "overlap" of the x-ray beam beyond the film on a side was 1.5 and 1.3 cm for the long and short dimensions for all film sizes.

GLOSSARY

ABSORBED DOSE - the amount of energy deposited in a medium by a beam of ionizing radiation. The special unit of absorbed dose is the rad which is equal to 0.01 joule/kilogram (or 100 ergs/gram).

ABSORPTION - the local deposition of radiation energy.

ABSORPTION UNSHARPNESS - the unsharpness in the image due to variations in absorption throughout a three-dimensional structure, caused by the particular shape of that structure.

AIR GAP TECHNIQUE - a method of reducing scattered radiation to the film by separating the film and the object being examined by some distance.

ANODE - a positive electrode; in an x-ray tube, it is the TARGET for the accelerated electrons.

ARTIFACTS - see RADIOGRAPHIC ARTIFACTS.

ATTENUATION - the reduction in intensity of an x-ray beam as a result of absorption and scattering processes as it traverses matter.

AVERAGE GRADIENT - the slope of the characteristic curve between the end points of the useful range of densities. For radiographic film, the end points of the useful range are usually defined as 0.25 above base plus fog and 2.00 above base plus fog.

BASE PLUS FOG - the density of the film which has received no exposure and has been processed normally. The actual density is due to the film base opacity and any inherent fog due to age or storage conditions.

BREMSSTRAHLUNG (German for braking radiation) - one method by which x rays are generated. In this process a fast-moving electron comes close to and is deflected by the positively charged nucleus of an atom. The kinetic energy lost by this electron is emitted from the atom as an electromagnetic photon.

BUCKY - a moving grid; the movement is designed to prevent the imaging of the lead strips of the grid in radiographs.

CASSETTE - a lighttight film-holding case which keeps the x-ray film and intensifying screens in intimate contact.

CATHODE - a negative electrode; in an x-ray tube, it is the FILAMENT, at which free electrons are produced by THERMIONIC EMISSION.

CHARACTERISTIC CURVE - a curve expressing the relationship between radiation exposure to the film and the resulting film density. Also called the H-D curve after Hurter and Driffield who first described it, or the D log E curve for density (the ordinate of the graph) vs. log of the exposure (the abscissa).

CHARACTERISTIC RADIATION - discrete electromagnetic radiation released as electrons move from higher to lower electron energy shells in an excited atom.

COLLIMATORS - an x-ray tube attachment for restricting the size and shape of the primary beam. A VARIABLE COLLIMATOR consists of two (and sometimes more) sets of independently adjustable lead shutters at right angles to each other which provide a great variety of rectangular or square fields.

COMPTON EFFECT - an attentuation process for x or gamma radiation. In this process the incident photon interacts with a "free" or loosely-bound electron, transferring a portion of the photon's energy to the electron (termed a "Compton electron") as kinetic energy and the remainder to a newly created scattered photon which travels in a different direction than the incident photon.

CONES - metal tubes that are attached to the x-ray unit head to limit the field to a predetermined size and shape.

CONTRAST - see FILM CONTRAST, RADIOGRAPHIC CONTRAST, SUBJECT CONTRAST.

CONVERGENT LINE - the line along which the lead strips of a linear focused grid would intersect if the strips were extended above the grid to the focal distance.

CONVERGENT POINT - the point at which all of the lead strips of a crossed focused grid would intersect if the strips were extended above the grid to the focal distance.

CROSSED GRID - a grid composed of two linear grids, one on top of the other, with the grid lines of one perpendicular to the grid lines of the other.

DENSITY - the mass of substance per unit volume; see also OPTICAL DENSITY.

DETAIL - the small individual elements of an image corresponding to those of the subject; see also RESOLUTION.

DEVELOPMENT - the chemical reduction of the silver ions to metallic silver in the exposed photographically sensitive crystals of the film emulsion.

DIAPHRAGM - an x-ray tube head attachment consisting basically of a sheet of lead with a hole that determines the size and shape of the primary beam.

DISTORTION - the lack of proportionality in a radiographic image caused by three-dimensional objects being nonuniformly magnified due to the range of object-to-image receptor distances existing for each object.

ELECTROMAGNETIC RADIATION - the transmission of energy via photons that travel at the speed of light.

ELECTRON VOLT (eV) - the energy gained by an electron as it is accelerated through a potential difference of 1 volt.

EXPOSURE - a measure of the ionization produced in air by x or gamma radiation. The special unit of exposure is the roentgen which is equal to 2.58×10^{-4} coulomb of charge collected per kilogram of air exposed.

FILM CONTRAST - the contribution to the overall RADIOGRAPHIC CONTRAST visualized in a processed radiograph from the intensifying screen-film processing system. FILM CONTRAST increases (or decreases) the SUBJECT CONTRAST as the system converts the x-ray intensity variations emergent from the subject into visible images.

FILM DENSITY - see OPTICAL DENSITY.

FILM GRADIENT - a measure of the slope of the characteristic curve at any point.

FILM GRAININESS - a type of radiographic mottle caused by the size of the individual silver halide crystals and their tendency to clump during development.

FILM SPEED - a measure of the exposure necessary to produce a given optical density, generally 1.0 plus base plus fog.

FILTRATION - the process of placing radiation absorbers in the primary beam to selectively remove low energy photons before they reach the patient.

FIXATION - the removal of undeveloped silver halide crystals after development of the film to prevent gradual darkening, which would otherwise occur as the silver ions are slowly reduced with time.

FLUORESCENCE - the emission of light radiation from a substance within 10^{-8} seconds following the absorption of radiation from another source. In radiological practice, fluorescent screens are used both for radiographic imaging (intensifying screens to expose film) and for fluoroscopic imaging (screens which may be viewed directly, or indirectly through an electronic image intensification system).

FOCAL DISTANCE - in a focused grid, the perpendicular distance between the grid and the convergent line or point.

FOCAL SPOT - that area of the target (anode) which is bombarded by electrons from the cathode.

FOCUSED GRID - a grid in which the lead strips are slightly angled such that lines drawn through the strips would intersect above the midline of the grid, i.e., the lead strips focus in space.

FOGGING - a grayness added to radiographs due to exposure to some type of undesired noninformation-carrying radiation, e.g., light in the darkroom or scattered x rays.

FULL-WAVE RECTIFIED CIRCUIT - an x-ray tube circuit in which the negative portion of the ac cycle is electronically inverted, producing a circuit that varies between a potential of zero and a positive maximum with no negative portion.

GAMMA - the gradient of the linear portion of the characteristic curve.

GEOMETRIC UNSHARPNESS - the loss of detail due to penumbral effects.

GRID - a device constructed of alternating strips of lead and a radiotransparent medium (such as aluminum, wood, or plastic) which are oriented in such a way that most of the primary radiation will pass through the grid between the strips while most of the scattered radiation will intersect the lead strips and be absorbed.

GRID CUTOFF - the loss of primary radiation that results when the focal spot is not positioned on the convergent line (for linear focused grids) or at the convergent point (for crossed focused grids).

GRID RATIO - the ratio of the height of the lead strips to the thickness of interspace material.

HALF VALUE LAYER (HVL) - the thickness of any material that is required to reduce the intensity of a given beam by one half.

HALF-WAVE RECTIFIED CIRCUIT - an ac circuit in which the negative potential portion of the cycle is eliminated by means of a rectifier, the voltage remaining at zero for that period of the cycle.

H-D CURVE - see CHARACTERISTIC CURVE.

HEEL EFFECT - a consequence of the angle of the target of the tube which results in greater radiation intensities on the cathode side as compared to the anode side of the radiation field.

INHERENT FILTRATION - the filtration provided by all the parts of the x-ray tube through which the beam must pass—the glass tube envelope, the insulating oil, and the x-ray window.

INTENSIFICATION FACTOR - the ratio of the exposure required to produce an image without the aid of intensifying screens to the exposure required to produce an equivalent image with intensifying screens.

INTENSIFYING SCREEN - a device for converting the energy of the x-ray photons into light photons, thereby increasing the efficiency of radiographic image formation and reducing the x-ray exposure necessary to produce an image.

INTENSITY - the total energy passing through an area per unit area per unit time.

INVERSE SQUARE LAW - a mathematical relationship that describes the decrease in radiation intensity with increasing distance from a point source of radiation. It is expressed by the equation

$$\frac{I_1}{I_2} = \frac{d_2^2}{d_1^2}$$

where I_1 is the intensity at distance d_1 from the point source
and I_2 is the intensity at distance d_2 from the point source.

IONIZATION CHAMBER - a device for measuring EXPOSURE by collecting the electrical charge carried by the ions produced in a finite air volume by the incident radiation.

IONIZING RADIATION - high energy electromagnetic radiation that produces ions as it passes through matter, e.g., x rays, gamma rays, and some energies of ultraviolet radiation.

keV (kilo electron volt) - the kinetic energy gained by an electron as a result of being accelerated through a potential difference of 1000 volts (equal to 1000 eV).

KILOVOLTAGE - the potential difference applied across an x-ray tube to accelerate electrons emitted by the cathode to the anode.

kVcp (kilovoltage constant potential) - the nearly constant potential difference applied across an x-ray tube by a voltage generator that is designed to decrease the voltage fluctuations. The term is usually reserved for those cases where the voltage fluctuation is held to less than 5%.

kVp (kilovoltage peak) - the maximum potential difference applied between the anode and cathode by a pulsating voltage generator.

LATENT IMAGE - the information contained by the sensitized "centers" in the film emulsion where some of the silver ions in the silver halide crystal have been converted to neutral silver atoms by the action of the incident radiation. The information cannot be visualized at this stage and must be developed in order to provide a visible image.

LATITUDE - the range of exposure levels that can be imaged on a film, more specifically, the range that provides useful optical densities.

LIGHT LOCALIZER - a light source in most x-ray unit heads to indicate the size and location of the primary beam.

LINE PAIR - a unit used to provide a quantitative measure of detectable resolution; defined as one opaque line and one space. A resolution of one line pair per millimeter means that lines 1/2 mm wide and 1/2 mm apart can be detected.

LINEAR GRID - a grid in which the length of the lead strips are all in the same direction. Linear grids may be focused or nonfocused.

MAGNIFICATION - the exaggeration of the image size compared to the actual object size due to the fact that the image-forming radiation emanates from a point source.

mAs (milliampere seconds) - a combination unit which is the product of the tube current (expressed in mA) and the exposure time (expressed in seconds). The total output of an x-ray tube is directly proportional to the mAs (or either of its components).

MONOENERGETIC - consisting of photons of a single energy, as applied to a beam of radiation.

MOTION UNSHARPNESS - the image unsharpness caused by movement of the patient or of the x-ray tube during the exposure.

MOTTLE - see RADIOGRAPHIC MOTTLE.

NONFOCUSED GRID - a grid in which the lead strips are all perpendicular to the face of the grid; also called a PARALLEL GRID.

OPTICAL DENSITY (O.D.) - a measure of the percentage of incident light transmitted through a developed film; it is defined by the equation

$$O.D. = \log_{10} \frac{I_o}{I_t}$$

where I_o = light intensity incident on the film
and I_t = light transmitted through the film.

PARALLEL GRID - see NONFOCUSED GRID.

PARTICULATE RADIATION - radiation which transmits energy from point to point in the form of the kinetic energy of moving particles of some mass.

PENUMBRA - the region of partial shadow at the periphery of the x-ray field that receives radiation from only a portion of the focal spot.

PHANTOM - a volume of material approximating as closely as possible the size, shape, nonuniform composition, density, and effective atomic number of tissue. Ideally, a phantom should mimic the appropriate body part with respect to the absorption of radiation.

PHOSPHORESCENCE - the emission of light radiation from a substance after a time delay of greater than 10^{-8} seconds following the absorption of radiation from some other source. If the time delay is less than 10^{-8} seconds, see FLUORESCENCE.

PHOTOELECTRIC EFFECT - an x-ray absorption process in which the photon interacts with a tightly-bound inner shell electron of an atom. Part of the energy of the photon is used to overcome the forces binding the electron to the atom, and the remainder is expressed as kinetic energy of the emitted electron (which is termed a "photoelectron").

PHOTOGRAPHIC DENSITY - see OPTICAL DENSITY.

PHOTON - a quantum of electromagnetic energy. The quantity of energy (in eV) carried by a photon is the product of its frequency in hertz (cycles/sec) and Planck's constant.

PLANCK'S CONSTANT - 4.1×10^{-15} electron volt-second.

PRIMARY RADIATION - the radiation emitted from the x-ray tube.

QUALITY - a term referring to the average energy of the x-ray beam.

QUANTITY - a term referring to the total number of photons in the x-ray beam.

QUANTUM MOTTLE - a type of radiographic mottle due to the statistical variation in the number of photons incident on any given area of the intensifying screen.

RADIATION - a mechanism by which energy is propagated from point to point through space or through matter.

RADIOGRAPHIC ARTIFACTS - any abnormal appearance on the film which is the result of improper storage, handling, exposure, or processing of that film.

RADIOGRAPHIC CONTRAST - the differences in optical densities between different portions of the radiograph which enable image details to be visualized. The final RADIOGRAPHIC CONTRAST visualized on the film is dependent on two independent factors, SUBJECT CONTRAST and FILM CONTRAST.

RADIOGRAPHIC MOTTLE - the nonuniform density of a uniformly exposed film due to quantum mottle, structure mottle, and film graininess.

RESOLUTION - the ability of an imaging system to define the fine details of an object.

RESOLUTION OF INTENSIFYING SCREENS - a measure of the maximum detail or smallest element detectable when using a film-screen combination.

ROENTGEN - the special unit of EXPOSURE. This is only defined for x or gamma radiation in air, and is equal to 2.58×10^{-4} C/kg.

ROTATING ANODE TUBE - an x-ray tube design in which the anode is a rotating disk. During an exposure the actual focal area is projected onto an annular region of the anode, thereby distributing the excess heat over a larger area, and therefore allowing more intense exposure techniques.

SCATTERED RADIATION - a type of secondary radiation composed of photons of lower energy than the incident photons which created them and which travel in a different direction. Scattered radiation is a product of the Compton effect.

SCREEN - see INTENSIFYING SCREEN.

SCREEN FILM - film made with thin emulsions that are specifically sensitive to either the blue or green light of fluorescent screens.

SCREEN UNSHARPNESS - the image unsharpness due to the size of the fluorescent crystals comprising the screens, the thickness of the screens, and the closeness of contact between the film and the screens.

SECONDARY RADIATION - any radiation in the beam which is generated as a result of interactions of the primary beam with matter. At diagnostic energies, it is primarily composed of scattered photons, Compton electrons, characteristic x rays, and photoelectrons.

SELF-RECTIFIED CIRCUIT - an x-ray tube circuit in which the x-ray tube itself serves as a rectifier and only the positive portion of the ac cycle is used; therefore, it is a type of HALF-WAVE RECTIFIED CIRCUIT.

SHARPNESS - see RESOLUTION.

SIGHT DEVELOPMENT - a manual method of film processing where the development time is determined visually; it is therefore subjective and variable and may involve the deliberate overexposure of the film (and patient) in order to save a few minutes of developing time.

SIMILAR TRIANGLES - two triangles in which corresponding angles are equal.

SPEED - see FILM SPEED.

STATIONARY ANODE TUBE - an x-ray tube design in which the anode is a single immobile structure.

STRIP DENSITY - in a radiographic grid, the number of lead strips per inch of grid.

STRUCTURE MOTTLE - a type of radiographic mottle due to variations in the structure of the intensifying screen.

SUBJECT CONTRAST - the intensity variations in the x-ray beam emergent from the subject, due to the differential attenuation throughout the x-ray field.

TECHNIQUE FACTORS (sometimes spelled TECHNIC) - technical factors which describe how the x-ray unit should be set and operated in order to produce a radiograph; these will include factors such as kVp, mAs, distance, and intensifying screen speed.

THERMIONIC EMISSION - the process by which free electrons are produced at the cathode of an x-ray tube when the filament is electrically heated so that the thermal energy imparted to the electrons is sufficient to overcome the atomic forces binding them to the atoms of the filament.

THREE PHASE X-RAY GENERATOR - a generator that combines three full-wave rectified circuits slightly out of phase with each other such that the tube voltage varies between 80% and 100% of maximum and never falls to zero.

TRANSMITTANCE - the fraction of incident light that is transmitted through the film.

UNSHARPNESS - loss of detail in a radiographic image.

X RAY - very short wavelength electromagnetic radiation which originates from the extranuclear part of an atom.

X-RAY SPECTRA - the relative distribution of different photon energies in a photon beam.

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