FILM-SCREEN RADIOGRAPHY RECEPTOR DEVELOPMENT

A HISTORICAL PERSPECTIVE

Perry Sprawls, Ph.D.

Content

1. Introduction and Overview

Radiographic receptors in which the image is recorded and displayed on photographic type film were used for more than a century after the introduction of x-ray imaging of the human body in 1895 by the physicist, Wilhelm Roentgen. Over this period of time there have been many innovations and developments in the design of the technology and clinical applications establishing radiography and other forms of x-ray imaging as a major medical procedure. With x-ray imaging being a physical process it has provided an opportunity for physicists to be major contributors in research and development along with providing scientific support for effective and safe clinical procedures. This provided a foundation for medical physics to develop as a major and highly-respected professionwith academic programs and degrees at universities and certification by professional organizations.

The history of screen-film radiography development is extensively documented and published in the many scientific papers on the various developments, textbooks of the period, and especially many historical review books and articles, often published on anniversaries of significant events. A selection of some of the most significant publications documenting the history is included in the bibliography at the end of this chapter. It is not our purpose to repeat what has already been extensively published. Our plan here is to develop an understanding of the issues that were the motivations for the research and developments that provided the historical foundation.

Over a century of research and development on film-based radiographicreceptors has produced greatly extended visibility within the human body with the lowest possible radiation exposure. That is what we will now explore beginning with some basic background.

Medical radiography is the process of producing fixed or recorded images of the internal structures, functions, and signs of disease or injury within the human body using x-radiation. Technology for the production of radiographs consists of two major components as illustrated in Figure 1: a source of the x-radiation consisting of an x-ray tube and associated electrical energy sources, located on one side of the body, and the image receptor located on the other. The historical development of x-ray tubes and related equipment is described in other chapters. Here we consider the receptor introduced in Figure 1.

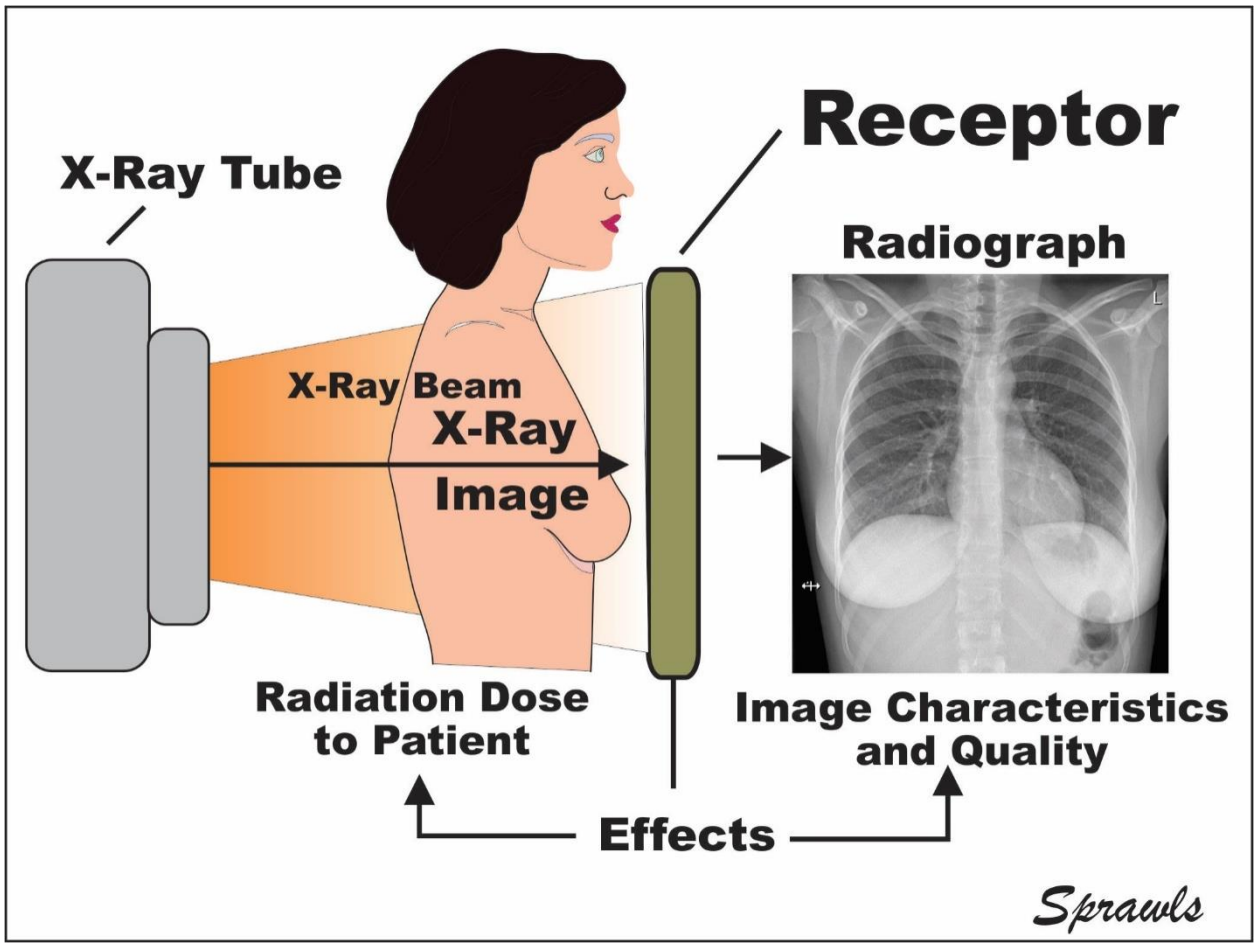

Figure 1. The general function of a radiographic receptor and the effects that are determined by design characteristics.

The receptor is the component that "receives" the invisible x-ray image coming from the patient's body,known as the latent image and converts it into a visible image.

Over the course of history there have been two very distinct and different types of receptors. The first, which was used for over a century, was based on a chemical process that formed images on sheets of photographic type film in contact with fluorescent screens and generally designated as *film-screen radiography*. The second was a physical method using digital electronic technology and designated as *digital radiography*.

In this chapter we trace the development of film-screen radiography from its origin with Roentgen's discovery, research, and demonstrations up to and including the science and technology associated with the final design characteristics at the time film-screen was replaced with digital technology. An overview of this evolution is shown in Figure 2.

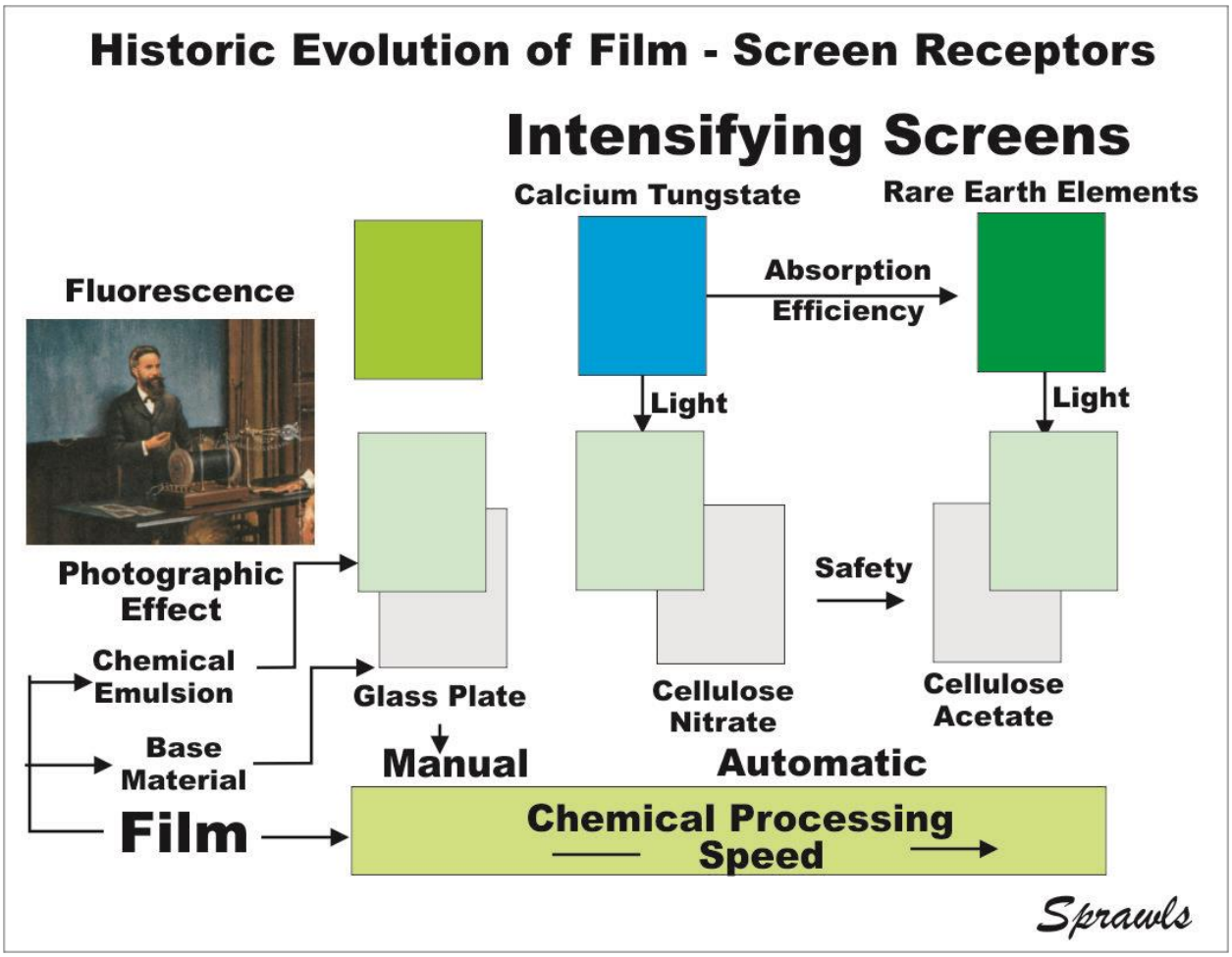

Figure 2. The major phases in the development and evolution of film-screen radiographic receptors.

The introduction of medical radiography to the world came when Roentgen gave a presentation describing his research finding on the characteristics of "a new kind of radiation" and demonstrated the process of imaging internal structures of the human body at the University of Würzburg on January 23, 1896. The news spread rapidly around the world and the process was repeated in many locations, usually in physics laboratories that already had the equipment for generating x-radiation (partially evaluated glass tubes and high-voltage electrical sources) that was being used for other purposes.

Photography was an established technology at this time and photographic plates were the available receptors.

Roentgen discovered and investigated two properties of the new radiation that were to be the foundation of radiographic receptors for well over a century. This was the radiation produced light in certain fluorescent materials, or phosphors, and also could form images in photographic materials. It is actually the combination of these two effects that produces radiographic images within a receptor and will be reviewed throughout this chapter.

The continuing research and development contributing to the evolution of film-screen receptors was driven by at least three factors:

- *Increased Image Quality* was a major factor to expand the scope of anatomical structures and pathologic conditions within the human body that could be visualized. This continued to increase the clinical effectiveness of radiography as a diagnostic method.
- *Reduced X-ray Exposure* to patients. This is an ongoing challenge because several elements of image quality depend on the quantity of radiation used. A significant effort in receptor development has been to increase the efficiency, or "quality-to-exposure" relationship.
- *Increased Efficiency and Productivity*. Images recorded on large sheets of film required considerable effort and labor in handling and especially storage and retrieval (archiving). Chemical processing of film consumed both staff time and effort and added a significant expense to the imaging process. A series of innovations relating to both design of film and the equipment for processing was a major factor addressing this limitation.

The purpose of a radiographic procedure is to provide *visibility* of the internal structures and conditions within the human body. However, visibility of specific objects within the body is determined by a combination of three major image characteristics: contrast, detail as limited by blurring, and visual noise as illustrated in Figure 3.

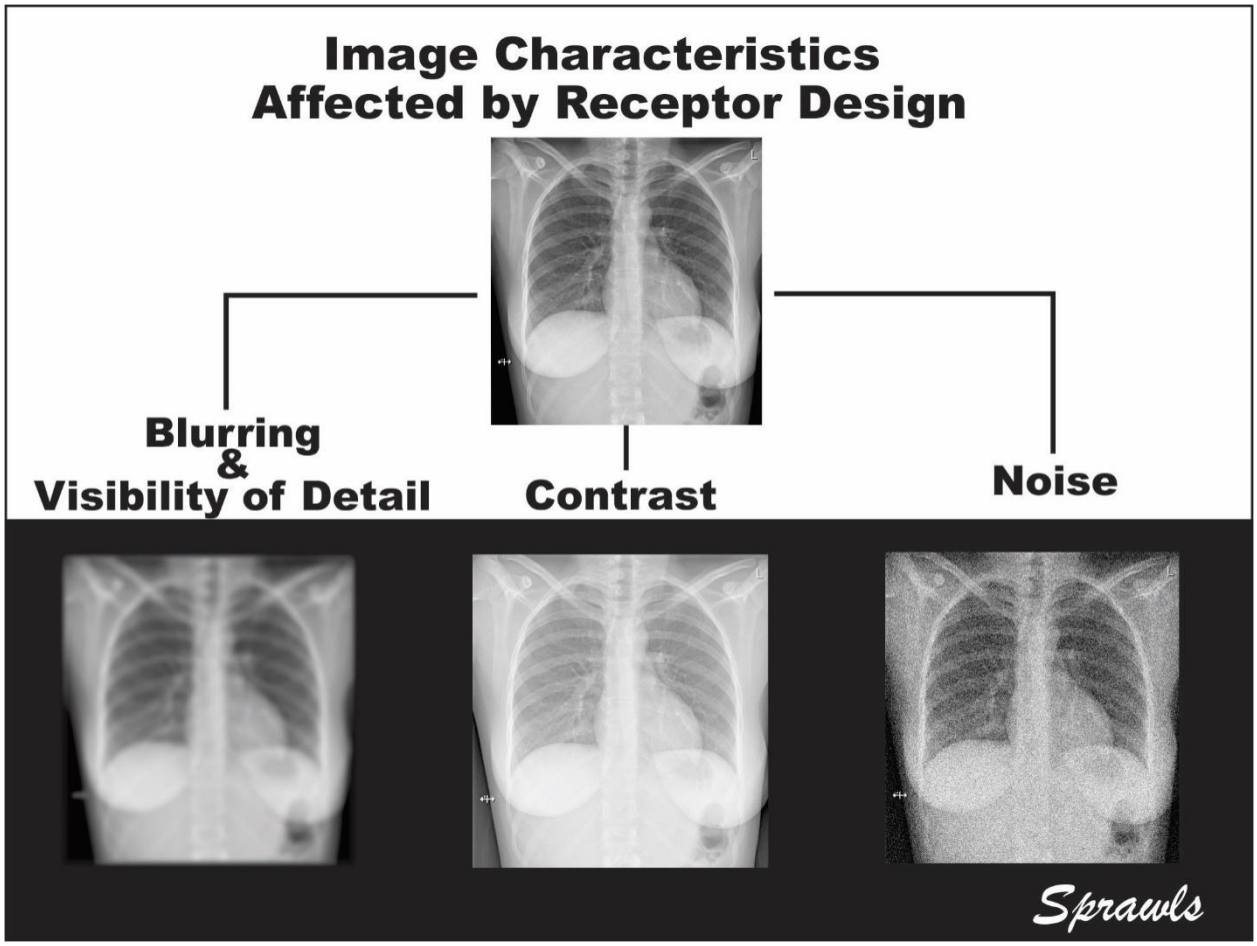

Figure 3 Three basic image quality characteristics that are affected by receptor characteristics and design.

Each of these specific characteristics has a direct effect on visibility of anatomical structures and conditions within the body. However, it becomes somewhat complex because of relations among the three characteristics and especially their relationship to the required x-ray exposure to form images. Each of these image characteristics and exposure requirements is determined by the design characteristics of a receptor. This has been the focus of research and development over many years.

The goal has been to produce images that provide the necessary visibility for specific clinical applications and with the lowest possible radiation exposure to the patient. While it is, and will always be, necessary to use certain quantities of radiation to achieve the required image quality for specific procedures there has been the continuing improvement in the *image quality-to- radiation exposure* relationship that has occurred with the many advances in receptor design.

The functions of a radiographic receptor are to first *absorb the x-radiation*, and then *convert* the x-ray image into some visible form. The major challenge throughout the continuing development of receptors has been to get the highest possible absorption in the thinnest possible layer of material within the receptor. Why is this so significant? First, high absorption decreases the quantum noise in relation to the required receptor and patient radiation exposure. Radiation that is not absorbed by the receptor does not contribute to image formation but does increase patient exposure. That is because it must be compensated for by increasing the exposure to the receptor and patient.

The absorption in the receptor is determined by a combination of three factors: thickness, characteristics of the material (density and atomic number, Z), and the x-ray spectrum. The research and development of receptors has focused on designs that provide a balance among these factors.

2. Glass Plates, the First Radiographic Receptor

At the time of Roentgen's introduction of radiography the practice of photography was well developed and photographs were produced with light-sensitive emulsions coated onto various materials including glass plates. Since these emulsions were also sensitive to x-radiation the coated glass plates became useful and available radiographic receptors. At that time the practice of photography was somewhat complex and required considerable materials, knowledge, and experience. It was the commercial photographers who had this capability and promoted radiography as a "new kind of photography" and opened studios for this purposed. Rather than going to a hospital or clinic for a radiograph a person could go to the local photographer. Photographers were already using large plates for portraits and these were appropriate for radiographs of anatomical regions including the chest.

While photographic emulsions are sensitive to and can form images from x-ray exposure, they are relatively thin and do not provide high absorption. This was one of the first major issues addressed in receptor development. The first was to design thicker emulsions specific for x-ray direct exposure and then the introduction of intensified radiography using fluorescent screens as described later.

Glass plates remained the base material for radiographs for many years, until the development of flexible and more convenient base materials when the receptor became known as a film rather than a plate. A radiograph on a glass plate is shown in Figure 4a and 4b(being developed).

Figure 4.a Radiographs recorded on a glass plates being chemically processed. They are rigid, fragile, and relatively heavy to handle
b. An early radiograph recorded on a glass plate.

Glass plates were used for radiography because they were the only practical materials available to support photographic emulsions at that time. Their extensive use in photography provided the experience and resources to support the early days

of radiography. However, they presented considerable challenges for use as radiographic receptors. These included being fragile, difficult to handle and store, expensive, and sometimes limited availability.

3. The Evolution of Film Base Materials

The considerable limitations of glass plates motivated the development of different base materials with the desirable characteristics of flexibility, transparency, and being relatively thin. It was the flexibility that was to make mechanical (often referred to as automatic) chemical development and processing of film possible to replace manual or hand processing. This was a major step in increasing productivity and improving image quality and consistency.

Cellulose Nitrate

In the 1910s glass plates were generally replaced with film bases composed of cellulose nitrate. This had many of the desirable properties but unfortunately was very flammable, resulting in some disastrous fires, especially in hospitals where large quantities of film were stored.

Cellulose triacetate-safe film

In the 1920s the nitrate flammable material was replaced with cellulose triacetate which was promoted as a safe, non-flammable, film.

Blue Tinted Film Base

In the 1930s it was discovered that adding a light blue tint to the film base provided improved viewing comfort with less eye strain than the completely clear and transparent film bases.

Reduced Base Light Crossover

This will be discussed later but with the films with emulsions coated on both sides and placed between two fluorescent intensifying screens an undesirable effect was light produced by the intensifying screen on one side passing through the film base and exposing the emulsion on the opposite side. Because the light could spread as it passed through the film base this added some blurring to the image. Over the years several approaches were developed to reduce light crossover. One was the development of film base materials that were less transparent to the light from intensifying screens but completely transparent to visible light for viewing images.

4. The Sensitive Photographic Emulsion

It is the relatively thin chemical emulsion coated onto the base that forms the image, commonly referred to as "the emulsion" because it consists of a suspension of many individual silver halide crystals within a supporting material. The recording and producing of an image, generally known as the "photographic process," by the silver halide crystals will be described later along with the chemical development that is a major phase of image formation.

Film Transparency and Optical Density

The emulsion coated onto the transparent base becomes opaque when it is exposed to radiation (either x-ray or light) and then chemically processed. The opaqueness can be quantified and expressed as *optical density*. The density value is inversely related to the amount of light that penetrates or passes through the film and is a logarithmic relationship. The exposure that forms an image can be over a large range of several decades (factors of 10) but the resulting density values are limited to a range of not more than 0 – 4 density units.

Densitometers are instruments for measuring the optical density at a specific point on a film by passing a small beam of light through it. They were used extensively for monitoring the variations in film density associated with the chemical processing in the context of quality control programs and for collecting data to plot graphs as described below.

Film Characteristic (H & D) Curves

The relationship of optical density to exposure determines the contrast characteristics of an image. Within a receptor it is the film that determines the contrast, the most predominant image quality characteristic. For a specific radiographic image the contrast is determined by a combination of three factors: the design of the film, the amount of exposure, and the conditions associated with the chemical processing. The performance of a film with respect to these three factors can best be expressed with a graph relating optical density to exposure as shown in Figure 5.

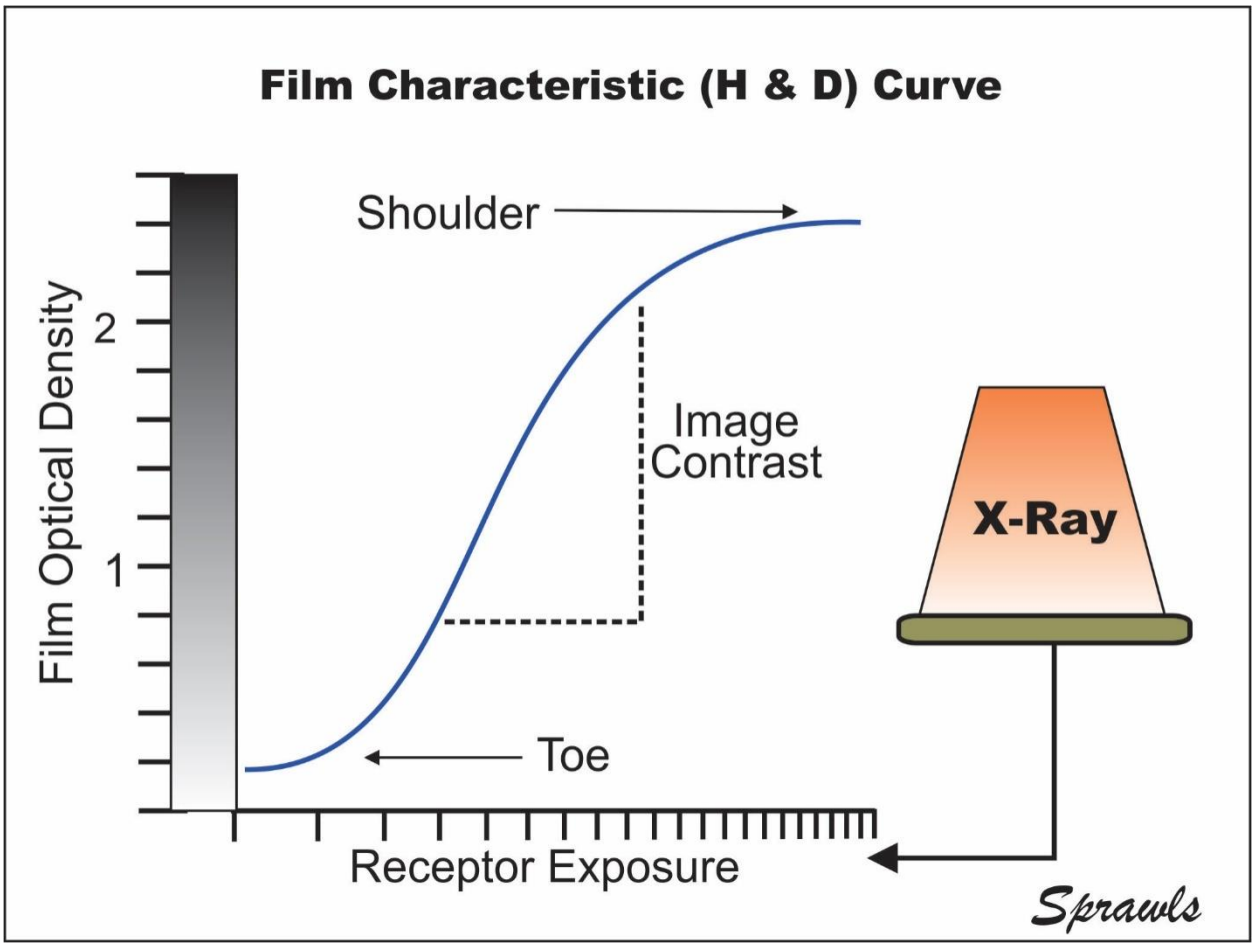

Figure 5. The characteristic (H & D) curve relating film 0ptical density to receptor exposure that is on a logarithmic scale.

This graphical method was developed for photographic film by Hurter and Driffield and carries their name, or initials H & D along with the name characteristic curve. The general contrast characteristics of a film represented by the curve are illustrated in Figure 5.

The usual method for producing a film characteristic curve is to expose a film to progressively increasing steps of exposure with an instrument known as a sensitometer, process the film, and then measure the density at each step with a densitometer.

The function of the film is to convert the image contrast coming from a patient's body into visible contrast and display it for viewing, typically on an illuminated view box. This conversion of exposure contrast into visible optical contrast is determined by the slope or gradient of the characteristic curve at each exposure value. For every film there are three distinct exposure ranges where the contrast formation is different. Maximum contrast is produced in the region representedby the steepest or greatest slope or gradient. This is a major characteristic of a film and determines which clinical procedure (chest, mammography, etc.) it is designed for. There are three mathematical factors that can be used to express this. The film *gamma* is the numerical quantity expressing slope or tangent at the steepest, or maximum contrast, point along the characteristic curve. It is expressed as the difference in density for a 10 to 1 exposure ratio. A specific film under specific processing conditions will have one gamma value. It is a carryover from photographic film but not easy to measure for x-ray film within radiology departments. Also, it expresses the contrast just at one point along the exposure scale, the point of maximum contrast. As shown, the slope and contrast varies over the exposure range and this has a significant effect on overall image contrast. The *average gradient* is one value expressing the "average" slope over the range with adequate slope to contribute to image formation. Values for the gamma and average gradient depend on the design of the film, from "contrast" to "latitude" type films, and with values generally in the range of 3 to 4.

The more practical unit, the *contrast factor*,is the density difference for a 2 to 1 exposure ratio. This is easily determined with conventional sensitometers and densitometers and is used in film processing quality control activities. The contrast factor can be determined for each point along the exposure scale.

The Toe and the Shoulder

As shown in Figure 5 there are two regions, corresponding to low and high exposures where the slope and contrast decreases and becomes zero. This is because of the chemical nature within the photographic process. At low exposure values, relating to the toe of the curve, there is not sufficient exposure to initiate the formation of any useful density.

Base Density and Fog

The optical density represented by the toe of the curve comes from several sources. The film base is almost, but not completely, transparent. There is some density of the base material which is generally below 0.15 density units. Fog is the term for density that is within the emulsion that is not associated with planned exposure during an imaging procedure. There are several possible sources. These include exposure from environmental radiation, ageing of undeveloped film, especially at high temperatures, and over development. Measurement of the base + fog density is one important action in a quality control program. It should generally be below 0.2 density units.

Maximum Density (D max)

At high exposure values there is a limit to the formation of additional density and this is represented by the shoulder of the characteristic curve. This occurs because all of the available silver halide crystals within the emulsion have been activated and converted to dark metallic silver. Over the years film has been designed to produce higher maximum density. This extends the range of exposure that can produce useful image contrast (latitude) but might require special viewing conditions with brighter illumination. This has been especially valuable in mammography.

Film Latitude

The latitude of a film is the range of exposure that will produce useful and visible density values, generally specified as from 0.4 to 2.75 density units as illustrated in Figure 6.

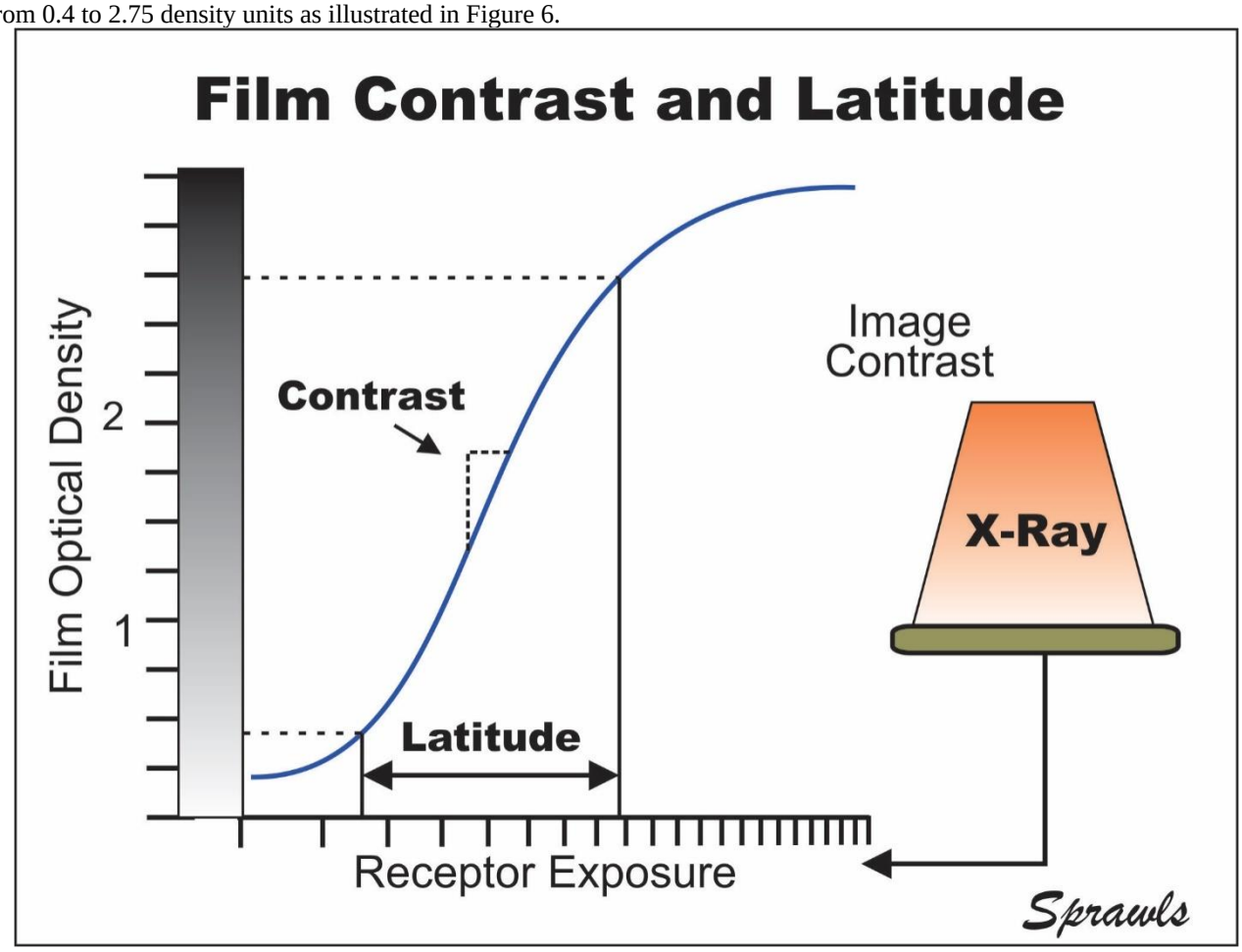

Figure 6. The latitude of film and its relation to contrast.

The latitude of a specific film is determined primarily by the emulsion design and chemical composition. It has always been one of the limiting factors of film for radiography. Film latitude is the general equivalent of dynamic range for digital

imaging systems. It is the range of exposure values to a receptor that can produce useful image contrast. Exposure outside the latitude range, either below in the toe or above in the shoulder, results in reduced or no contrast.

There are two major factors that can result in exposures outside of the latitude range and the loss of contrast. One is a mismatch of the exposure delivered to the receptor with what is actually required. This is generally referred to as an "exposure error" coming from two conditions. The most common was the selection of the technique factors, especially the quantities KV and MAS (in the units of kV and mAs) for a specific procedure. Automatic exposure control (AEC), also known as photo timing, contributed to reduced errors but was not always a solution. Others, and often less obvious, were variations in the exposure required by a receptor (its sensitivity or speed) caused by differences among receptor components and especially changing conditions in the chemical processing of film described later. All of these potential sources of exposure error were addressed in quality programs conducted by or under the direction of medical physicists.

The second factor contributing to reduced contrast in some areas of an image is the wide range of exposure coming from the patient's body because of variations in body thickness or density. The chest is an example. When the range of exposure extends beyond the latitude range contrast will be reduced. This was addressed by designing film with several different contrast-to-latitude relationships to fit specific clinical requirements.

5. Radiographic Film for Specific Clinical Applications

Throughout the history of radiography one of the constant challenges has been providing the correct exposure to a film to produce the appropriate image contrast. Contributing to this challenge has been both that of adjusting the exposure for each imaging procedure and also factors associated with the design and processing of the film that will be considered here. This relates to the contrast characteristics of film as illustrated in Figures 5 & 6. There is a limit to the range of exposure to a film receptor that will produce the desired contrast. Generally this must be within the film latitude, and also the characteristic curve gradient must be sufficient to produce the required contrast. These conflicting requirements have been addressed with advances in film technology and design of film with optimized characteristics for specific clinical applications, usually related to the anatomical regions being imaged. The specific challenge has been developing film that can produce the necessary high contrast and also have adequate latitude to respond to the range of exposure projected from the patient's body. There has been a variety of designs over the years but the three major types are illustrated in Figure 7.

General Radiography with Contrast Type Film

Film with similar contrast characteristics (H & D curve slope) were used for imaging most parts of the human body, including the skeletal system and the abdomen, This was generally referred to as "contrast" type film both to emphasize its ability to produce good image contrast and also to distinguish it from "latitude" type film used in other anatomical areas.

Chest Radiography with Latitude Film

The chest or thoracic area of the body is a special challenge in radiography because of the wide range of densities within. The lungs contain air and are large areas of low density very different from the much denser mediastinum containing the spine and heart. The problem is that this produces a wide range of exposure coming from the body and if this is greater than the film latitude there will be a reduction or loss of image contrast in some areas. Film designed to have relatively wide latitude was used for chest imaging.

Mammography Film

Effective imaging of the breast, especially to detect early-stage cancers, requires receptors with special high-quality characteristics compared to other radiographic procedures. These will be described in more detail later but here attention is given to the film, specifically the more advanced film design used for mammography. The breast is composed of soft tissue with generally similar physical density values that is the source of contrast for an image. The mammography process is developed with several features to produce high contrast. One is special x-ray spectra and the other is the design of the film described here.

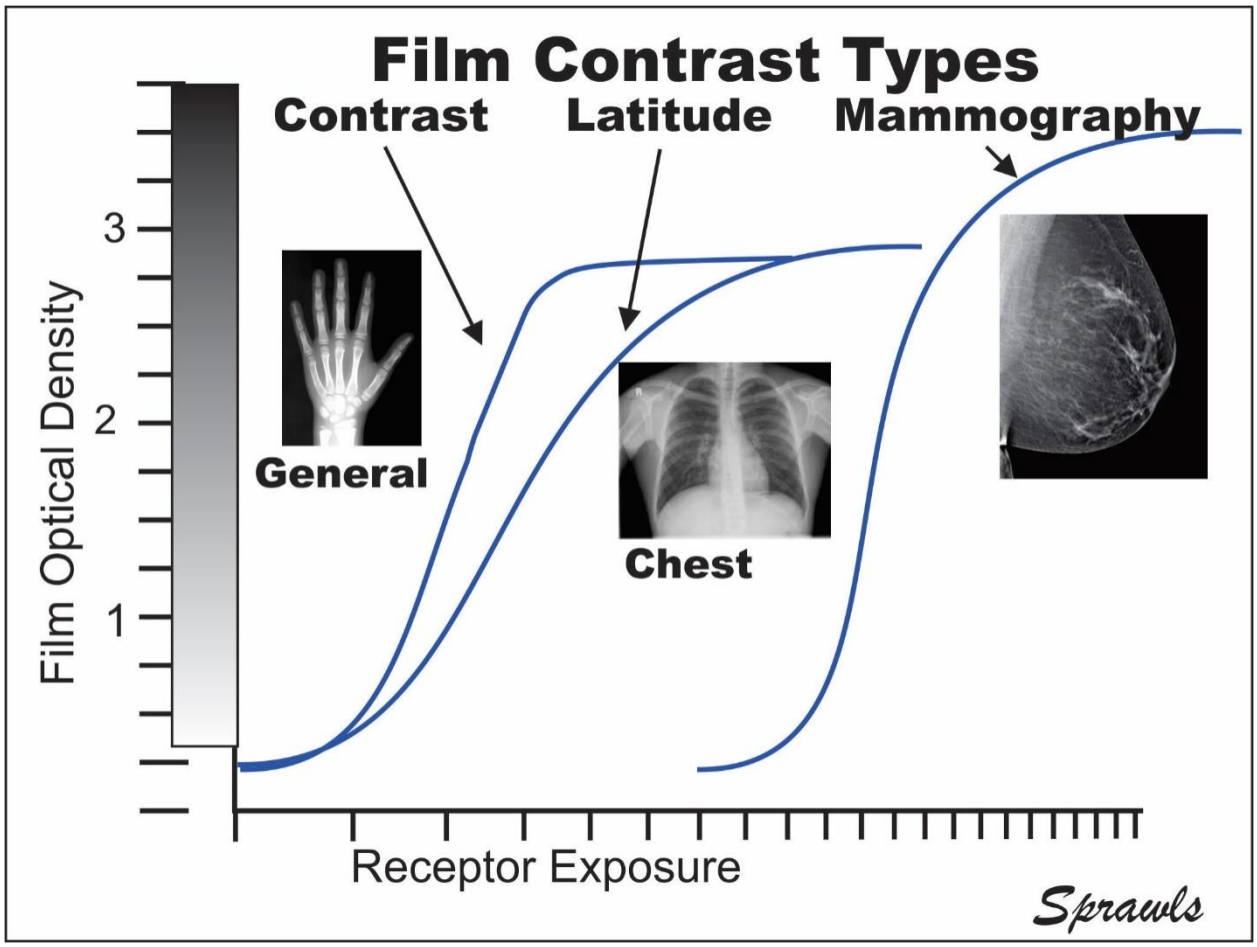

Figure 7. Different contrast characteristics of radiographic film for specific imaging procedures.

The requirements are for film with high contrast and wide latitude, the generally conflicting design characteristics. This is achieved in mammography film by having a high-contrast design (steep H & D curve slope) and extending the range into higher optical density or darkness values compared to other radiographic films as illustrated in Figure 7. This required that mammograms recorded on this type of film be viewed on special illuminators, or view boxes, that were brighter than those for other radiographic films.

Film Size and Shape

Four standard sizes and shapes for film-screen receptors (cassettes, screens, film) are:

8" x 10" (18cm x 24cm)
10" x 12" (24cm x 30cm)
11" x 14" (30cm x 35cm)
14" x 17" (35cm x 43cm)

The selection of which to use for a specific procedure was determined by the anatomical area to be images.

6. Radiographic Image Viewing

Images on transparent film were viewed by placing a source of light behind them. This was generally a flat illuminated surface, an illuminator, or more commonly known as a "view box" as illustrated in Figure 8.

Figure 8. Radiologist, Dr. Britton Gay, at Emory University viewing a radiograph in front of a view box.

Viewing Luminance (Brightness)

The performance of the human visual system is heavily dependent on the brightness of the image or objects being viewed.This limits the ability to visualize both small objects (detail) and objects with low contrast. Image viewing is the last but very important step in the total imaging process. Measuring the brightness of view boxes and taking corrective actions was an important of a quality control program. For general radiography a view box luminance of 1,500 cd/mm^2 was typical. Usually there was a small light, known as the "hot light" that would be used to view through dense areas in a film. Some film designed specifically for mammography had a higher maximum density and the images were much more dense or dark the conventional radiographs. This requires a brighter view box of approximately 3,000 cd/mm^2 or higher.

7. Chemical Processing of Film

Perhaps the most demanding aspect of film-based radiography was the chemical processing required to produce the images. It required time and effort by the staff, was a significant expense, and had significant and often undesirable effects on both image quality and potential patient x-ray exposure to patients. Because the chemical process is subject to considerable variability, good practice required quality control programs to maintain image quality and reduce the potential of unnecessary radiation exposure.

The formation of a visible image on film is a two-step process. The first is exposing the film with some form of radiation that produces the so-called "latent" or invisible image. The second step is the chemical processing that converts the invisible latent image into a visible image on the film. This is generally known as the "photographic process."

The Photographic Process

Film density is produced by converting silver ions into metallic silver causing each processed grain to become black. The process is illustrated by the sequence of events shown in Figure 9.

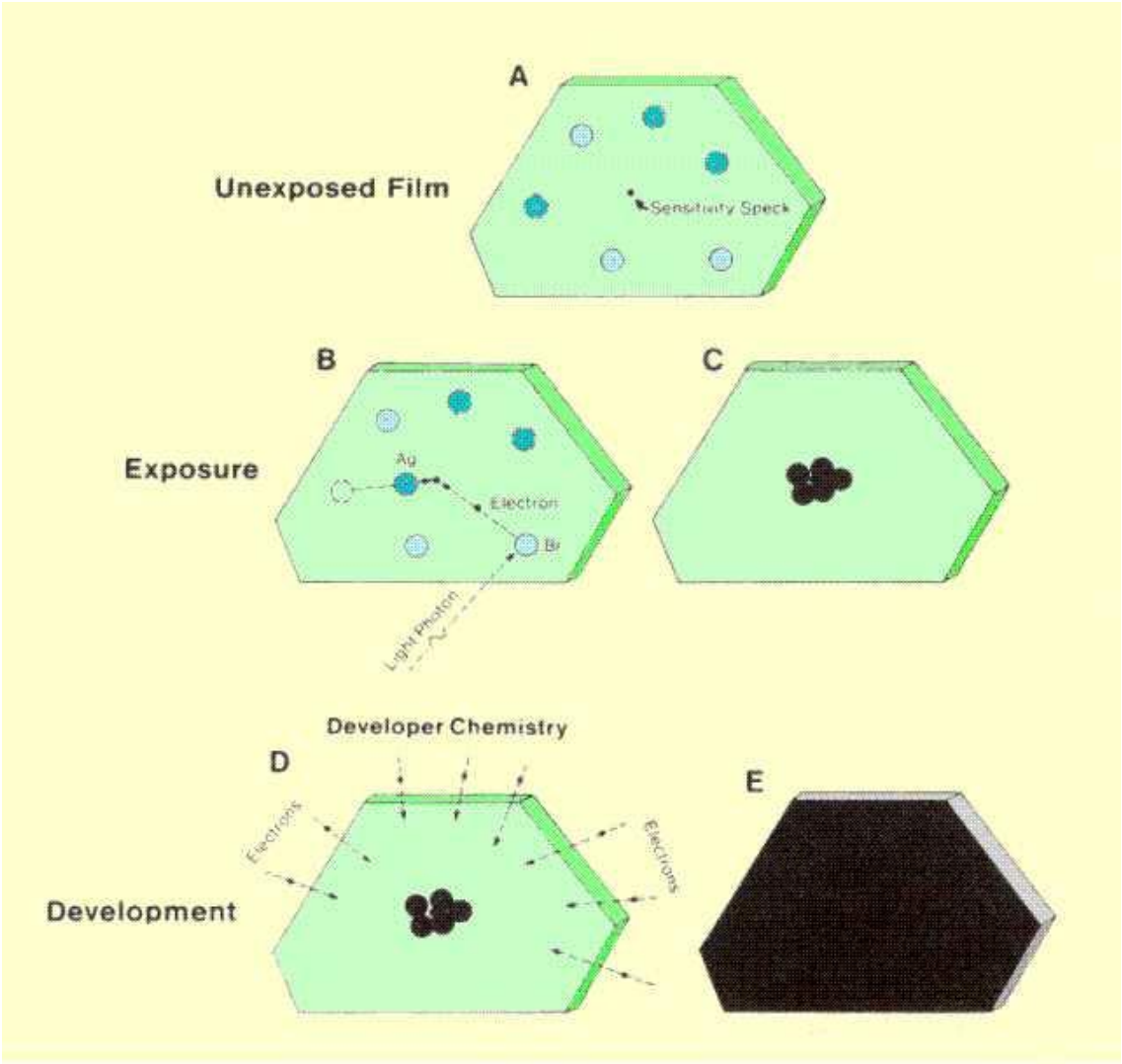

Figure 9. Sequence of events that convert silver halide grains into black metallic silver

Each film grain contains a large number of both silver and bromide ions. It was probably Louise Daguerre in France who first established this process around in 1839. The silver ions have a one-electron deficit, which gives them a positive charge. On the other hand, the bromide ions have a negative charge because they contain an extra electron. Each grain has a structural "defect" known as a sensitive speck. A film grain in this condition is relatively transparent.

The Processing Cycle

The chemical processing of an exposed film to convert the invisible latent image into a visible image consists of four steps as illustrated in Figure 10

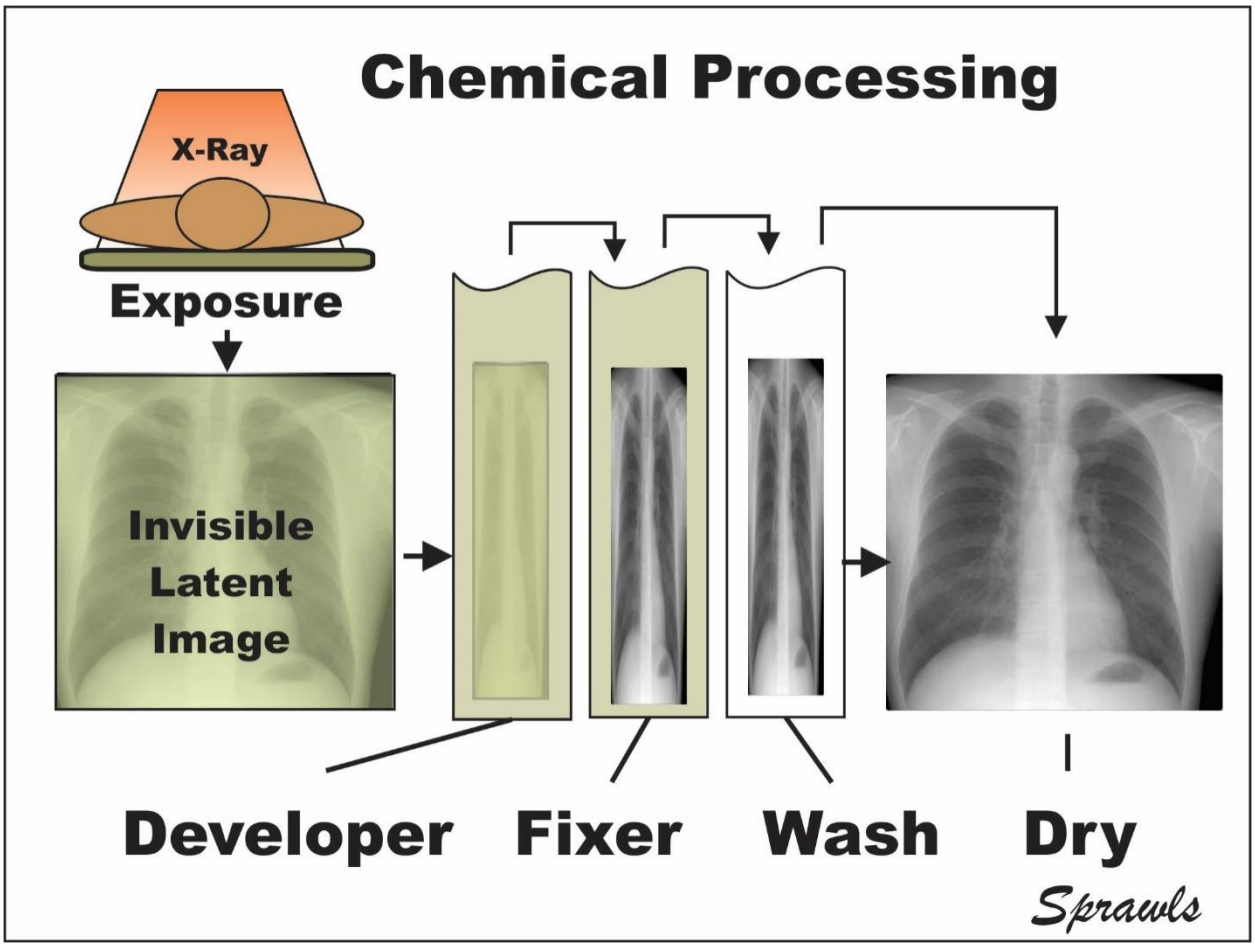

Figure 10. The series of steps in the chemical processing of radiographic film.

Developer

The invisible latent image is converted into a visible image by the chemical process of development. The developer solution supplies electrons that migrate into the sensitized grains and convert the other silver ions into black metallic silver. This causes the grains to become visible black specks in the emulsion.

Fixer

After leaving the developer the film is transported into a second tank, which contains the fixer solution. The fixer is a mixture of several chemicals that perform the following functions.

Neutralizer

When a film is removed from the developer solution, the development continues because of the solution soaked up by the emulsion. It is necessary to stop this action to prevent overdevelopment and fogging of the film. Acetic acid is in the fixer solution for this purpose.

Clearing

The fixer solution also clears the undeveloped silver halide grains from the film. Ammonium or sodium thiosulfate is used for this purpose. The unexposed grains leave the film and dissolve in the fixer solution. The silver that accumulates in the fixer during the clearing activity can be recovered; the usual method is to electroplate it onto a metallic surface within the silver recovery unit.

Preservative

Sodium sulfite is used in the fixer as a preservative.

Hardener

Aluminum chloride is typically used as a hardener. Its primary function is to shrink and harden the emulsion.

Wash

Film is next passed through a water bath to wash the fixer solution out of the emulsion. It is especially important to remove the thiosulfate. If thiosulfate (hypo) is retained in the emulsion, it will eventually react with the silver nitrate and air to form silver sulfate, a yellowish brown stain.

Dry

The final step in processing is to dry the film by passing it through a chamber in which hot air is circulating.

Controlling the Development Process

The chemical processing of film to produce a visible image is a complex process consisting of several functions as described above. The first phase, development, is especially critical because it is subject to significant variation that can affect the quality of an image and indirectly x-ray exposure to patients.

As a film is placed in the developer solution the process of producing a visible image begins. It is a continuing process for about 25 seconds in the more recent systems where the transport speed is well regulated. The rate of the development action is determined by a combination of factors that can be the source of instability and variability leading to development errors, either under- or over-development. The desired level of development is when all of the exposed silver halide grains are converted to black silver contributing to visible film density.

The level, or completeness, of development is determined by the combination of time in the developer solution and the rate of the developing action. When mechanical or automatic processors became available the time was well regulated and became less of a variable, especially when compared to manual/hand processing. The rate of development is determined by design composition of the chemistry and how it matches specific emulsion characteristics, to what level has the chemistry been depleted and replenished, and the temperature of the developer solution. In automatic processors the temperature is controlled by a thermostat but that could be set at the appropriate temperature. Processing test films exposed with a sensitometer and the resulting densities measured with a densitometer is a standard quality control procedure for monitoring the level of processing.

If a film is under-developed some of the exposed grains do not result in visible density with two undesirable effects, reduced contrast and reduced sensitivity (speed). The significance of the reduced sensitivity is that it might be compensated for by increasing the x-ray exposure to the patient.

If a film is over-developed some of the silver halide grains that were not exposed will be converted into visible density with two undesirable effects. One is the reduction in image contrast and the other is an increase of density in the regions of low exposure that is known as fog. The characteristic curve shown in Figure 11 shows the effects of variations in the level of development.

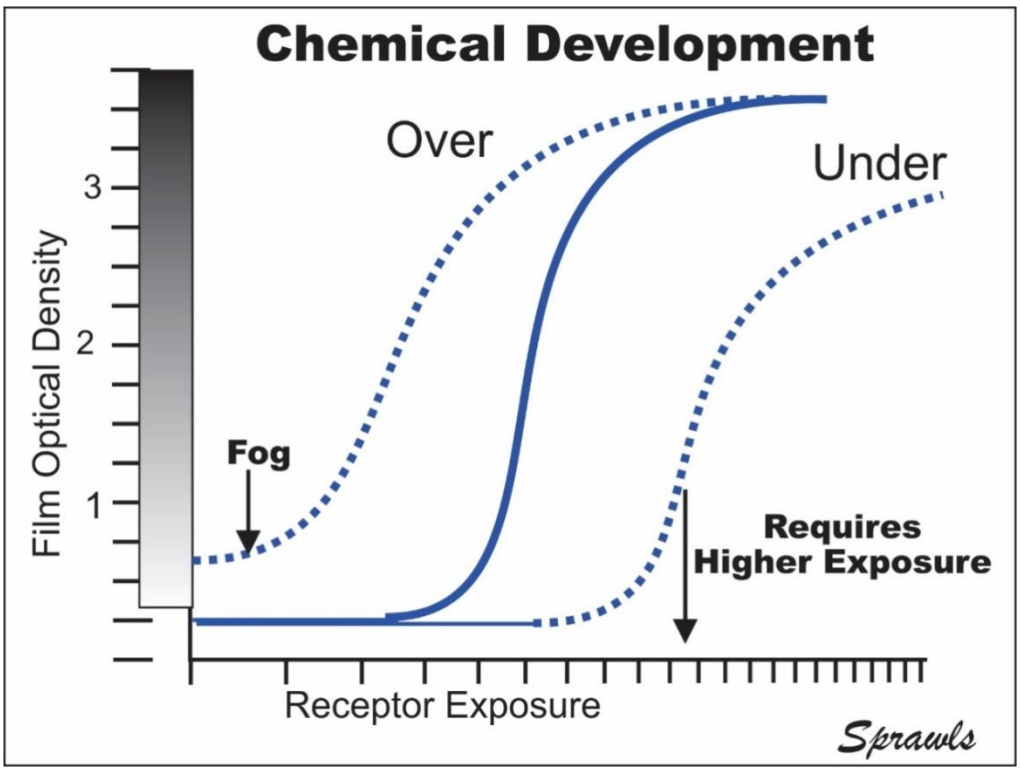

Figure 11. The effects of incorrect levels of development on film characteristics.

The chemical processing of film, especially the development phase, was generally the most unstable and variable part of the radiographic imaging process. In the early days when film was processed by manually placing it in and removing from the developer solution the time was a variable. With machine (often called automatic) processing the time was generally well regulated so the variation was in the *rate of development.* This was determined by the combination of two conditions, the composition of the developer chemistry and the temperature.

Full development of film required chemistry that was formulated to match specific film emulsions (not always achieved) and replenished as the developer chemistry was consumed in the ongoing process. In processors the developer was automatically replenished by pumping a small amount of new chemistry in as each film passed through.

Because the chemical processing of film was a major factor in both image quality and x-ray exposure requirements it was a very important quality control activity usually conducted by or under the direction of medical physicists. The usual procedure was to expose a test film with a sensitometer, process it, and then measure the resulting densities with a densitometer. The values were compared to reference values and also charted over time to monitor consistency.

8. Intensified Radiography

Even though the silver halide crystal emulsion can be exposed by x-radiation and form an image the sensitivity is very low in comparison to exposing with light. This is because the thin emulsion in not a good x-ray absorber and also the way in which the silver halide crystals require exposure by several individual photons. The energy of one x-ray photon is equivalent to many light photons. Therefore, for the same amount of energy delivered to a silver halide film the effect and image formation will be much greater if the exposure is with light rather than by x-radiation.

Although a few radiographic procedures continued to use direct film exposure, such as dental and industrial, intensified radiography became the common method.

The process of intensified radiography is illustrated in Figure 12.

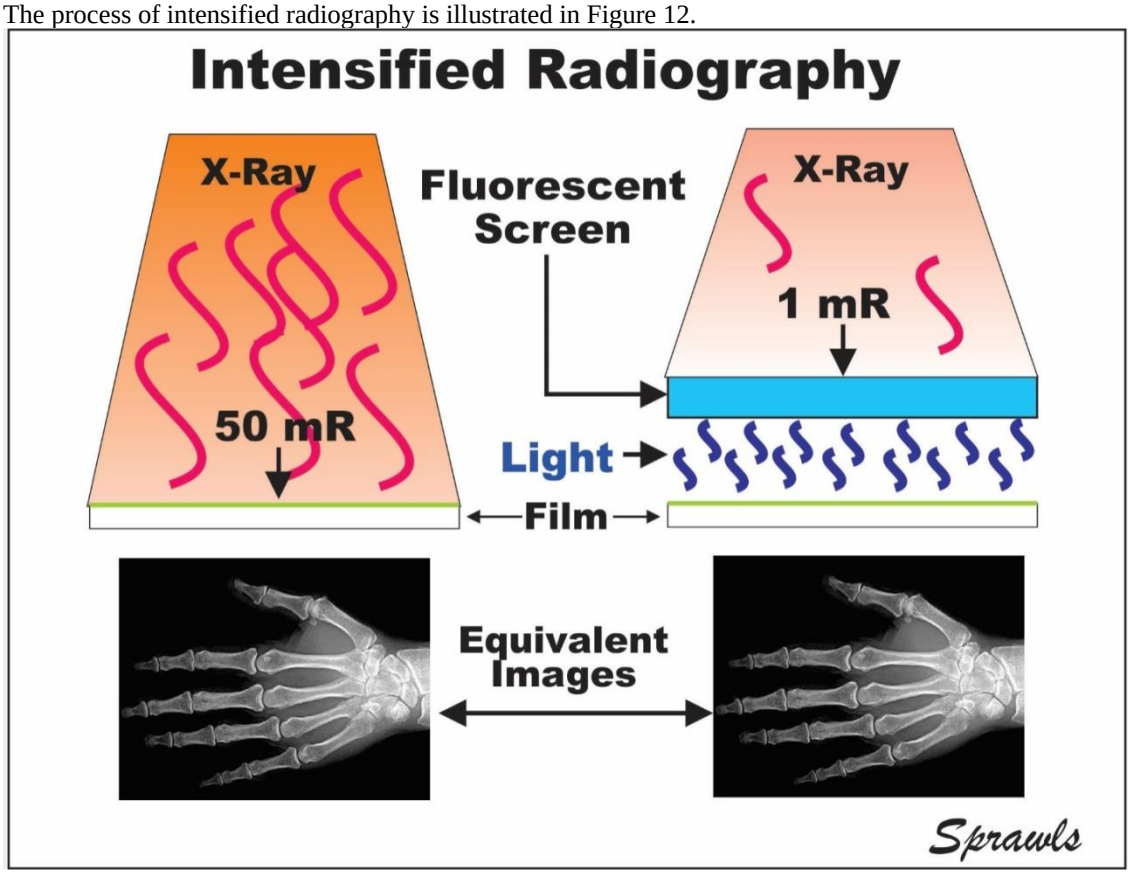

Figure 12. Using a fluorescent screen to increase, or intensify, the exposure to film from x-radiation.

An intensifying screen is a sheet of fluorescent material, or phosphor, placed in contact with the film. The size and shapes of intensifying screens matched that of the films and cassettes described earlier.The light produced within the screen from x-ray exposure is much more effective in exposing the film and producing an image compared to direct x-ray exposure.

Intensification Factor

The contribution of an intensifying screen to film exposure can be expressed as the *intensification factor* which is the ratio of x-ray to light exposure required to produce the same photographic effect or image. While these values were not generally useful for adjusting actual exposures in clinical practice they do demonstrate the great advantage in using intensifying screens. Values depend on the design characteristics of the screens such as thickness and composition as described later. A value of 50 is used in Figure 12 as an example. While this illustrates the great value in using intensifying screens to reduce exposure to patients it does not provide adequate information on the actual exposure required by radiographic receptors to produce an image.

Receptor Sensitivity and Speed

A major characteristic of every radiographic receptor is the x-ray exposure it requires to produce an image. This is expressed as either a *sensitivity* or *speed* value. Values depend on design characteristics of both the film and the intensifying screens and extend over a relatively wide range as shown in Figure 13.

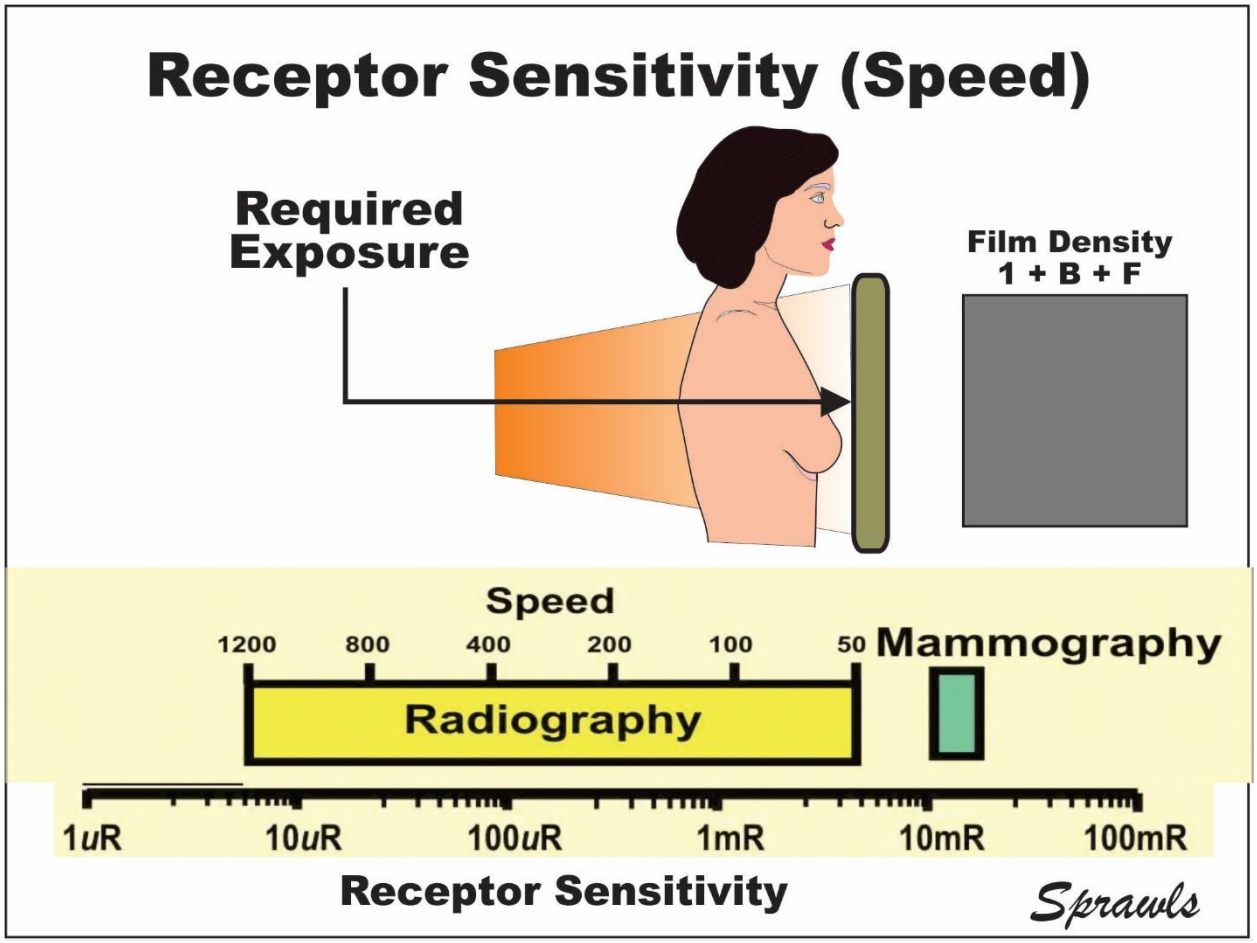

Figure 13. Range of exposure values required by receptors to form an image.

The standard procedure is to express the exposure requirement of a receptor as the exposure that produces a film optical density of one density unit above the base + fog density (1+B+F). Base plus fog density corresponds to the toe of the characteristic curve shown in Figure 5. A density value of one unit above the base-plus-fog is relatively close to the middle of densities visible in a typical radiograph and provides a reasonable reference for comparing procedures with respect to exposure to patients.

The *sensitivity value* is the actual exposure required to form the reference density value, 1+B+F, on a film. It can be measured and is useful for comparingexposure requirements of general radiography with other methods including mammography and fluoroscopy.

Receptor *speed* is a concept carried over from photography where it is used to express the exposure requirements of film. Increased speed implies that a film or receptor is responding faster and therefore requires less total exposure.

For radiographic receptors speed is not a precisely defined or measurable quantity but is more of a relative quantity for comparing receptors. At some time a specific screen-film receptor was designated as "par speed" and assigned a speed value of 100. Other receptors are compared to this to determine speed values. A general relation of speed and sensitivity values is given by:

Sensitivity (mR) = 128/speed.

Intensifying Screen Blurring and Visibility of Detail

The advantage of using intensifying screens is the great reduction in x-ray exposure required to produce an image compared to exposing film directly. As indicated in Figure 13 receptors using intensifying screens were available over a wide range of sensitivity or speed values. The question is why not always use the more sensitive receptors to reduce exposure to patients? The reason is that intensifying screens add blur to the image that results in reduced visibility of detail.

The amount of blurring is generally determined by the thickness of a screen which also affects its sensitivity. This is because thinner screens absorb less of the radiation and require more exposure to produce an image. The major factor in selecting the appropriate intensifying screen for a specific clinical procedure is this inverse relation between sensitivity and image quality. The general effect of screen thickness on both exposure requirements and image detail is illustrated in Figure 14.

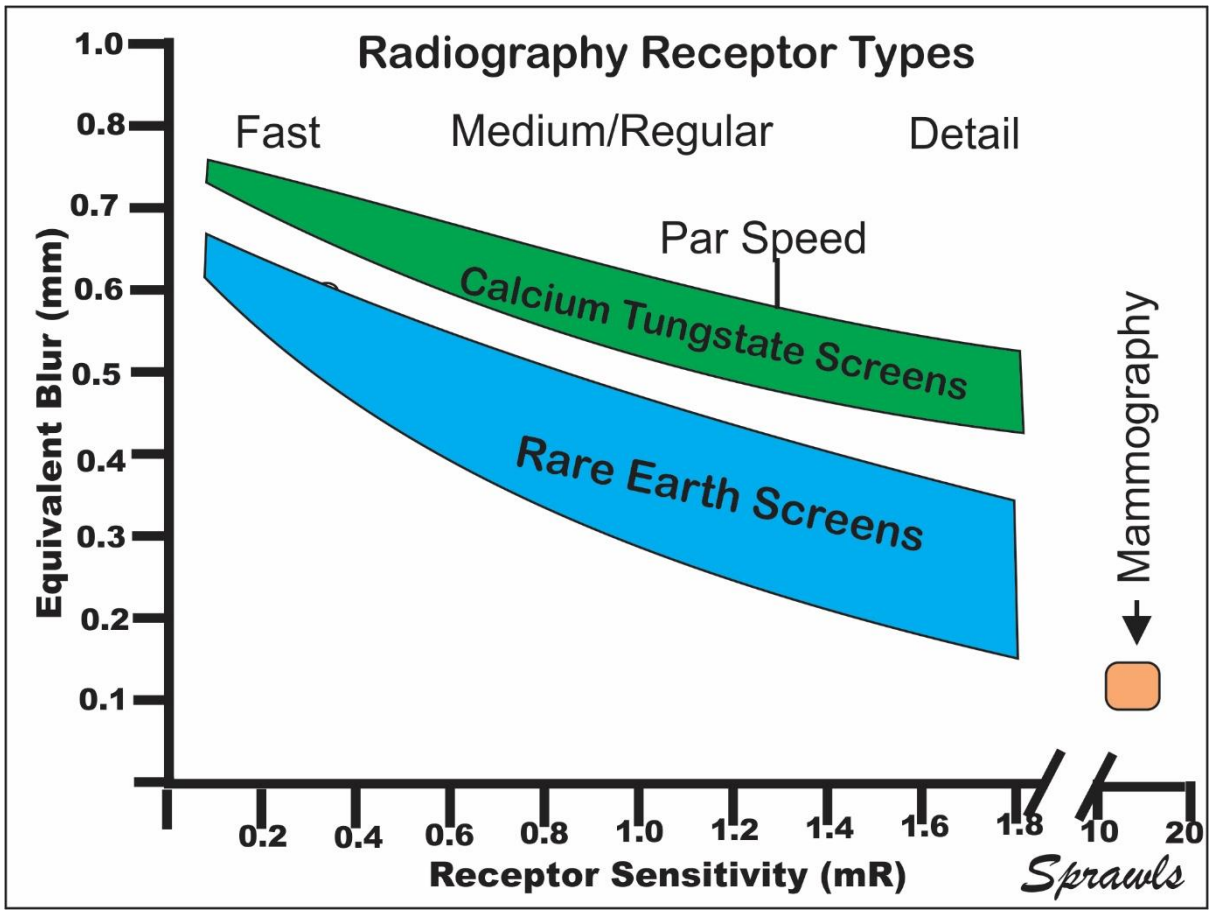

Figure 14. The general relationship between image detail and exposure requirements for the film-screen receptors available to an imaging facility. Also shown is the advantage of the transition from calcium tungstate to rare-earth intensifying screens.

Most intensifying screen manufacturers had commercial or trade names for their various screens. Most followed a general generic classification into three major types with names emphasizing the advantage, either high image quality or reduced exposure to patients. The three types were detail, par, and high speed. Figure 14 shows a general comparison and how each type relates to the thickness of the screen.

Light produced by the x-radiation occurs throughout the thickness of the screen. Light produced away from the side of the screen in contact with the film spreads before reaching the film. It is this spreading of light within the thickness of a screen that produces the blurring. In general, the amount of blurring increases with screen thickness. Thinner "detail" screens produce less blurring and better image detail but absorb a relatively small fraction of the x-radiation. Therefore, a higher exposure must be used to produce an image compared to the thicker "high speed" screens.

The blur produced within an intensifying screen generally has a Gaussian profile, or point spread function, as illustrated. For the purpose of radiographic system analysis and comparing screen blur to focal spot blurring it is appropriate to use *equivalent blur* values. This is the dimension of a blur with a uniform intensity distribution that has the same effect on visibility as the actual Gaussian distribution. For film-screen receptors equivalent blur values are calculated from modulation transfer function (MTF) curves generally provided by the manufacturers. Values are obtained for x-ray tube focal spots when measurements are made with a star test pattern. In a digitized image pixel size corresponds to an equivalent blur value. Table 1, discussed later, compares the equivalent blur values, speed numbers, and exposure sensitivity for receptors provided by one manufacturer, Kodak, in the 1990s.

A continuing design and development goal for intensifying screens has been to increase x-ray absorption to reduce exposure required while minimizing screen thickness to reduce blurring…the two conflicting requirements.

A common method for achieving this is the use of dual-screen receptors and film with sensitive emulsion on both sides as illustrated in Figure 15.

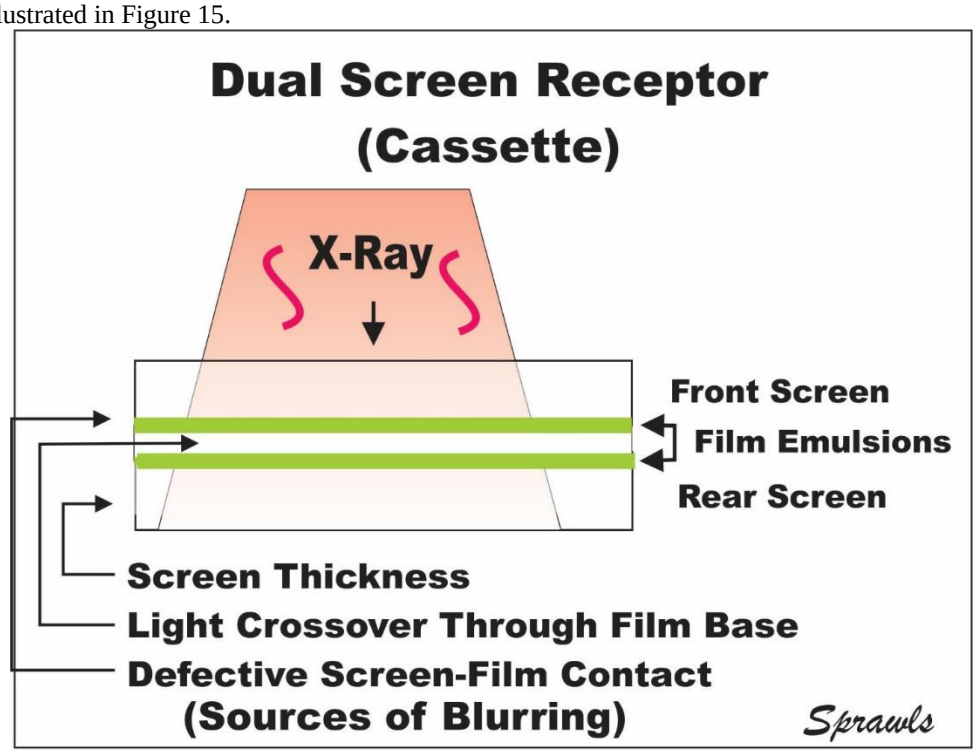

Figure 15. The typical radiographic receptor consisting of film with sensitive emulsion on both sides placed between two intensifying screens.

The advantage of this design is it provides the x-ray absorption of the two screen thicknesses combined but the blurring is related to just one screen thickness.

Dual screen receptors were used for most radiographic procedures with the exception of mammography where one thin screen and single-emulsion film is used to produce images with high detail—a requirement in mammography for the visualization of very small calcifications, one of the signs of cancer.

The dual-screen receptor does provide a significant advantage with respect to the "detail to dose" relationship but it introduces an additional, generally small, source of blurring. That is the possibility of some of the light produced by one of the screens passing through the film base and exposing the emulsion on the other side. Over the years several developments have addressed this problem. One has been to have base materials that are less transparent to the wavelength (color) of light produced by the screens. Another was the development of tabular, or flat, silver halide crystals that decreased light passing through the emulsion and into the film base.

A third potential source of blurring is defective contact between the film and screen surfaces. If there is some space, even very small, light can spread and produce blurring. This is an abnormal condition that might occur within defective cassettes and tested for in the context of quality control programs.

9. Radiography Image Noise

Visual noise, sometimes referred to as mottle, is an undesirable characteristic that reduces visibility of some anatomical and pathologic features, especially those with low contrast that often includes small objects. In radiography there are two specific and different sources of noise--structural and quantum.

Structural Noise

Structural noise is produced by the granular, or grainy, elements within the screens and film. Intensifying screens are in the form of many small crystals. Film is an emulsion containing individual silver halide crystals. If these individual elements are visible in an image it appears as a form of noise. In photography it's the individual silver halide grains that are the potential source of noise that is most commonly referred to as "grainy" photographs. Developments have produced both screens and films with less structural noise and in modern radiography it is not the predominant source of noise.

Quantum Noise

In radiography, along with other x-ray imaging methods, the predominant source of image noise is from the random distribution of the x-ray photons actually absorbed in the receptor, quantum noise. Since the amount of quantum noise is inversely related to receptor (and patient) exposure it is a major factor in managing radiation dose to patients. An appropriate procedure technique is when the quantum noise level has been set to produce just the necessary image quality for a specific clinical procedure, and not any lower. Reducing the noise beyond that results in unnecessary exposure to the patient.

In film-screen radiography the quantum noise level is determined by the characteristics of the receptor that has been selected for a specific procedure. The major factor determining the noise is the concentration of photons (exposure) actually absorbed in the receptor. This is the lowest photon concentration anywhere along the imaging process and is known as the "quantum sink" as illustrated in Figure 16.

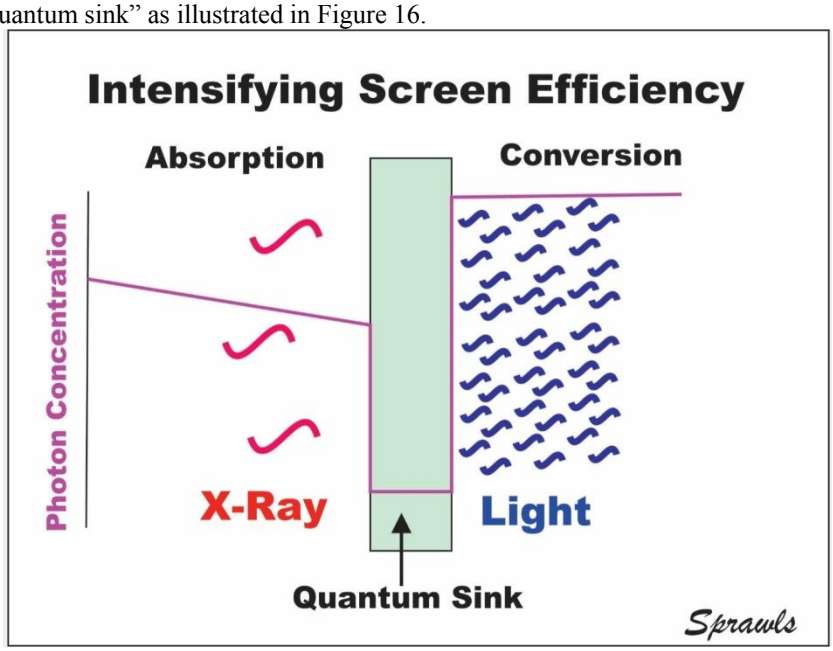

Figure 16. The two efficiencies of an intensifying screen and the quantum sink.

There are efficiency values associated with each of the two major functions of an intensifying screen; *absorption* of the x-radiation and *conversion* to light. Both are determined by the design (thickness and composition) of the screens. An increase in both efficiencies provides the advantage of increasing receptor sensitivity (speed) and reducing exposure to patients but can have an adverse effect on image quality.

The best image quality with the lowest patient exposure is obtained with quantum sink at the highest possible value representing the highest concentration of absorbed photons.

Conversion Efficiency and Film Sensitivity

A combination of two factors can reduce the quantum sink to a lower value for a specific receptor input exposure and increase the quantum noise. One is the screen x-ray-to-light conversion efficiency. Increasing this would make it possible to expose film and form an image with less x-radiation but the lower concentration of absorbed photons would increase quantum noise. In the development of intensifying screens the effort is not to get the highest possible conversion efficiency but a value that provides a balance between patient exposure and image quality, specifically quantum noise.

The sensitivity or speed of the film also affects the quantum sink. Using a more sensitive or higher speed film that requires less light reduces the quantum sink value and increases quantum noise.

While it was possible to develop radiographic receptors that require less x-ray exposure using either screens with higher conversion efficiencies or film with greater sensitivity these would not be useful because of the high noise.

Absorption Efficiency

The first function of an intensifying screen is to absorb the x-radiation. A design goal is to absorb a large fraction of the radiation because what is not absorbed is "wasted" and contributes to increased patient exposure but not to image formation. The fraction absorbed is determined by three major factors. One is the screen thickness described earlier that contributes to image blurring. The other two factors are the chemical composition of the screen and the x-ray spectrum which must be considered together.

10. Intensifying Screen Composition

The chemical composition and physical structure of intensifying screens have developed over the years with the continuing goal of improving image quality with reduced x-ray exposure. This has been divided into two very distinct eras based on the phosphor or fluorescent materials used in the screens, calcium tungstate and the rare earth elements.

Calcium Tungstate

Soon after Roentgen's discovery and development of the radiographic process calcium tungstate was found to be an effective fluorescent material for converting x-radiation into light and used as intensifying screens. The very productive inventor, Thomas Edison, and his staff were investigating many substances with fluorescent properties in their efforts to develop light sources. This experience contributed to the selection of calcium tungstate for use as an x-ray converter. Calcium tungstate, CaWO4, is a compound with several desirable properties. It is fluorescent when exposed to x-radiation, can be formed into thin sheets of relatively consistent and stable composition, and tungsten with a relatively high atomic number (Z=74) is an effective x-rayabsorber. While the introduction of calcium tungstate intensifying screens was a major contribution to radiography because of the reduction in x-ray exposure required to form images there were continuing issues with image quality.

Carl V. S. Patterson continued the development of screens with significant improvements. In 1916 he introduced screens composed of synthetic calcium tungstate that had several advantages over the natural form. *The Patterson Screen Company* also developed and produced fluoroscopic screens including the handheld fluoroscope that was popular during the early days of x-ray imaging. In 1943 *Du Pont* Company acquired the *Patterson Screen Company*.

Even with improvements in composition and the physical characteristics of calcium tungstate intensifying screens a continuing limitation was absorption efficiency. With the necessity of keeping screen thickness relatively low to control blurring the absorption of x-radiation was also relatively low. A contributing factor was this: with an atomic number of 74 tungsten has an absorption K edge at 69.4 keV. The significance is that much of the x-ray spectrum, especially when using medium and low KV values, is below the K-edge energy where absorption is diminished. It was this characteristic that provided an interest in developing other fluorescent materials.

Rare Earth Elements and Intensifying Screens

A major innovation in screen-film receptor technology beginning in the 1970s was the conversion from calcium tungstate to fluorescent materials composed of some of the rare earth elements. These included:

• yttrium oxysulfide
• lanthanum oxybromide
• lanthanum oxysulfide
• gadolinium oxysulfide.

Rare Earth Elements

The "rare earths" are a group of 17 chemical elements that have a variety of magnetic, luminescent, and electrical properties that contribute to their value in many modern technology applications. At least two, lanthanum and gadolinium,had properties making them effective elements for intensifying screens. They are not used alone but in compounds with additional elements as activators. The compounds had the desirable fluorescent yields contributing to good receptor sensitivity but it was their lower atomic numbers in relation to calcium tungstate that was a major factor. The lower atomic numbers placed their photo-electric absorption K edges at lower energies as illustrated in Figure 17.

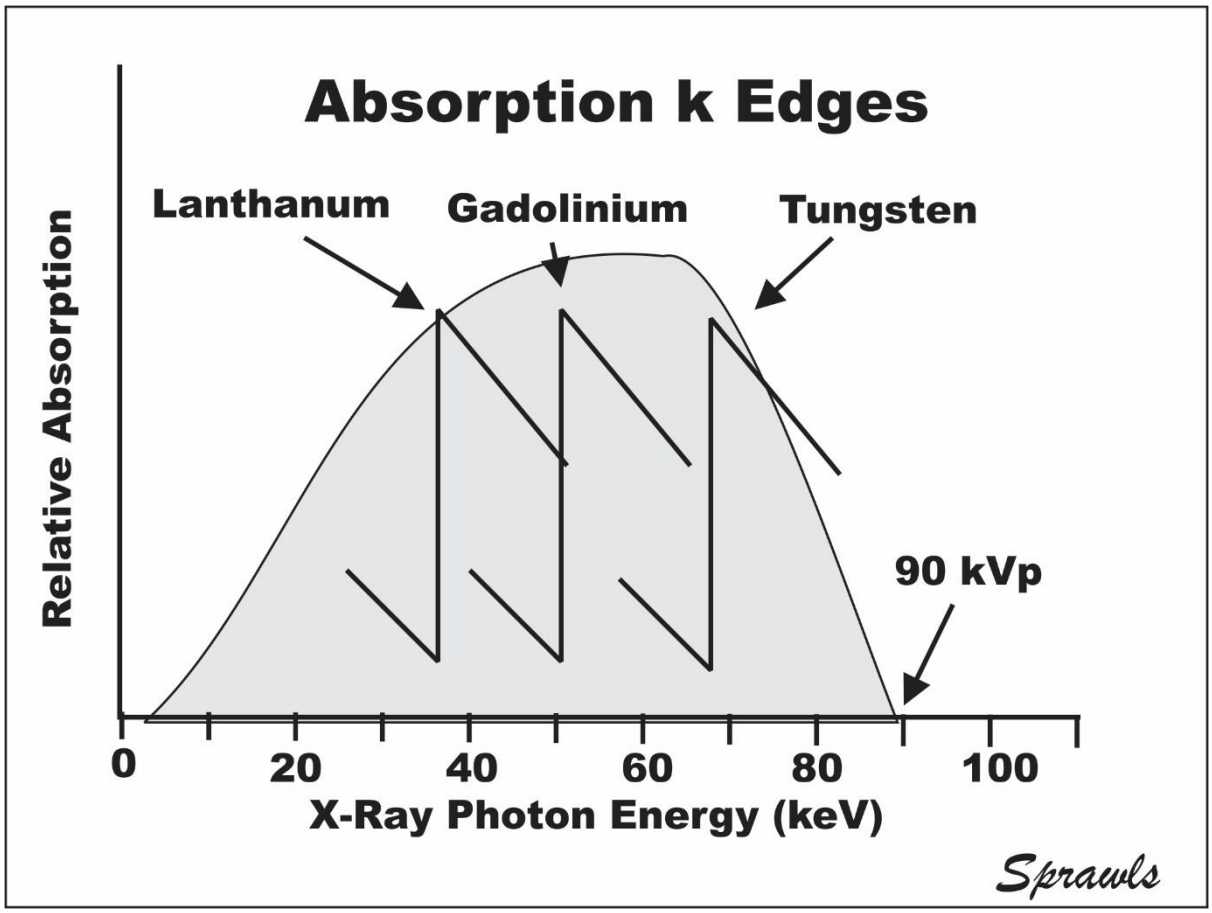

Figure 17. Intensifying screen material absorption **k edges** relative to x-ray spectrum produced at 90 kVp.

A major advantage in transitioning to the rare earth elements for intensifying screens was the increased absorption compared to calcium tungstate. Now the same absorption efficiency could be achieved with thinner screens that produced less blurring and better image detail with less exposure.

11. Advances in Film Science and Technology

Throughout the history of film-based radiography the basic photographic process using silver halide crystals continued. However, research and development continued to produce many advances in design and optimizations for a variety of clinical applications

A major film design change was required with the introduction of rare earth screens. The rare earth screens produced light in the green spectrum and different from the blue light produced by calcium tungstate. The green-sensitive film for use with rare earth screens also required changes in the color of the safe lights used in darkrooms for film processing.

12. The Final Radiographic Receptor Design and Characteristics

Film-screen radiographic receptors benefited from many advances and innovations for over a century to achieve the major goal of higher image quality with lower radiation exposure. However, with the development of digital technology the several limitations of film-based radiography contributed to its decline as a practical diagnostic procedure. The advantages provided by digital radiography were many. A major one was the elimination of the large quantities of film that required manual handling beginning with the loading into the receptor cassettes, chemical processing, arranging for viewing by radiologists, storage and archiving where they could be retrieved. Moreover, film radiography was subject to errors in exposure and variations in the chemical processing that produced problems with image quality. These were greatly reduced with digital imaging. A specific factor was when an image was captured on film and chemically processed it could not be adjusted or changed. With digital radiography the recorded image can be electronically processed to produce an image for viewing with optimized characteristics, especially contrast, for all clinical procedures. And perhaps the greatest advantage is that digital radiographs can be stored, retrieved, and transmitted to other locations for viewing very quickly.

At the conclusion of the film-screen era as the major type of radiographic receptor, the medical profession had a choice from a variety of film-screen combinations. This provided the opportunity to select a receptor with quality characteristics (contrast, blur/detail, and noise) that was optimum for specific clinical procedures, ranging from chest radiography to mammography, and could be balanced with the radiation exposure required to deliver the necessary image quality.

Of the two components of a receptor, film and intensifying screens, film was the major consumable produ

ct and financially significant for both the film industry and the medical facilities. It was generally an expensive product, partially because of its silver content and precise production conditions, and it was a consumable product that could be used only one time. For the most part, the providers of radiographic receptors were industrial organizations with a history and experience in the development and manufacturing of film for photography and photocopying purposes. These included *Kodak*, *DuPont*, *Fuji*, *Agfa*, and *3M*. They also produced intensifying screens that were compatible with the film and provided a choice of image characteristics.

As the major film-screen era was coming to a close and giving way to digital receptors several of the companies attempted to develop those products, but with marginal success. It was the equipment companies that had the technical background and experience and also the digital receptors were often just another component of the imaging systems. Also, since film and processing chemistry was a large consumable market that contribute to the success of the film companies that was no more.

Table 1 illustrates the range of receptors available from one provider, *Kodak*.

The names for the various receptors are the manufacturer's brand or trade names. They do give some indication of the general characteristics.

The inverse relationship between blur (image detail) and sensitivity (speed) is demonstrated here. This is for the most part determined by the thickness of the intensifying screens. Also shown is that receptors using some specific intensifying screens, for example *LANEX Medium*, can have several different sensitivity (speed) values depending on films they are used with. It is the sensitivity or speed of the film that affects the level of quantum noise. Using a higher speed film reduces patient exposure but at the cost of increased noise.

The receptors for mammography were single thin screens combined with film with emulsion on just one side. This was to produce images with very small blur values to provide better visualization of the very small calcifications that are valuable signs of some breast cancers. However, the required exposure, receptor sensitivity, is much greater that for other radiographic procedures.

In summary, over more than a century, film-based radiographic receptors evolved from a simple photographic emulsion on a glass plate to an extensive collection of film and screen combinations to choose from. The many innovations and developments greatly increased image quality with reduced x-ray exposure. The choice among the different combinations as illustrated in Table 1 provided the opportunity to select receptors that were the most optimum for various clinical requirements.

Receptor (KODAK Screen/Film)	Representative Equivalent Blur Value (mm)[1]	Relative Speed [2,3,4,5]	Approximate Receptor Sensitivity[6] (MR)
General Radiography [2,3]			
LANEX Fast/Ortho G, L, C	0.76	600	0.21
LANEX Fast/T-MAT H/RA	0.66	1200	0.10
LANEX Fast/T-MAT G/RA, L/RA, S/RA	0.66	600	0.21
LANEX Regular/Ortho G, L, C	0.64	400	0.32
LANEX Regular/T-MAT H/RA	0.53	800	0.16
LANEX Regular/T-MAT G/RA, L/RA, S/RA	0.53	400	0.32
LANEX Regular/T-MAT C/RA	0.53	400	0.32
LANEX Medium/Ortho G, L, C	0.55	250	0.51
LANEX Medium/T-MAT H/RA	0.44	600	0.21
LANEX Medium/T-MAT G/RA, L/RA, S/RA	0.44	300	0.43
LANEX Medium/T-MAT C/RA	0.44	250	0.51
INSIGHT HC/INSIGHT Film[7]	0.28	350	0.37
INSIGHT Standard/INSIGHT Film[7]	0.28	250	0.51
Extremities [2,4]			
LANEX Fine/Ortho G	0.41	80	1.60
LANEX Fine/T-MAT G/RA	0.23	80	1.60
LANEX Fine/EKTASCAN M (single screen)	0.14	40	3.20
Mammography [5]			
MIN-R/MIN-R M	0.14	100	16.0
MIN-R/MIN-R E (extended cycle)	0.14	150	10.7
MIN-R/MIN-R H	0.14	160	10.0

[1] The equivalent blur value is a measure of the amount of image blurring produced by the receptor. It is similar, in effect, to focal-spot size with respect to determining visibility of anatomical detail. Values are determined from MTF data measured in the laboratory.
[2] Medium-speed calcium tungstate screens and KODAK X-OMAT RP Film are arbitrarily assigned a speed of 100.
[3] Relative speeds are based on the average value of radiographs of three phantoms: (1) pelvis at approximately 70 kV without scatter; (2) chest at approximately 80 kV with scatter; and (3) chest at approximately 125 kV without scatter.
[4] Based on radiographs of an extremity phantom exposed at approximately 60 kV with scatter.
[5] Determined from matched density radiographs of a breast phantom, molybdenum target tube, 28 kVp, single MIN-R Screen/MIN-R M Film arbitrarily assigned a relative speed of 100.
[6] Based in part on Sprawls, P. Jr.; *Physical Principles of Medical Imaging*, Rockville, MD, Aspen Publishers, Inc., 1987.
[7] Determined at density 1.8.

Table1. Film-screen combinations arranged by image quality characteristics and exposure requirements.

Chronology: A Century of Radiography Receptor Developments in Review

Before the Discovery

The discovery of "a new kind of radiation", x- or Roentgen radiation, as it was to become known, followed by the intense research by Roentgen in 1895 demonstrated the capability to image the anatomical structures within the human body and gave birth to the practice of medical radiography. Its rapid spread to other institutions and countries was possible because the necessary technology, including photography, fluorescent materials, evacuated glass tubes for electrical experiments, and high-voltage sources had been developed and was available. This was the foundation on which radiography was built and enhanced over the next 100+ years.

1890s

This was a landmark decade for radiography. Roentgen discovered x-rays and demonstrated the process of radiography. Carl Schleusner manufactured the first glass plates for radiography. *Koda*kintroduced first paper for x-ray purposes and Thomas Edison recommended calcium tungstate for fluoroscopic screens. Michael Pupin reported screen-film radiograph and May Levy made radiographs using double emulsion coated film between two fluorescent intensifying screens

1900s

Glass plates produced for general photography were the available receptors for radiography but their limitations, requiring high x-ray exposure and image quality defects, was a continuing concern.

1910s

During this period the industry was continuing the development and manufacturing of plates designed for radiography that contained emulsions with increased absorption of x-radiation and required less exposure. *Kodak* Introduced film on a flexible cellulose nitrate base and also double emulsion film. Carl V. S. Patterson developed fluorescent intensifying screens with improved characteristics to overcome many of the problems experienced with earlier attempts to use screens. He also introduced the cassette using two screens with double emulsion film.

1920s

The *Patterson Screen Company*introduced fluorescent screens with protective coating for cleaning. *Kodak*introduced film with cellulose acetate base to improve fire safety.

1930s

*DuPont*introduced an x-ray film with blue tinted base to improve viewing comfort that became the standard type of film throughout the industry. *Patterson Screen Company*introduced *Patterson Par Speed screens*. This became the reference to which other screens were compared. *Ansco*introduced a direct x-ray exposure film for some specific clinical applications. *Fuji* began producing x-ray film.

1940s

*Pako*introduced an automatic film processor that mechanically dipped sheets of film into the series of processing solutions.

1950s

*Kodak*introduced the roller transport process in which film was moved continuously through the several processing steps…a major innovation.

1960s

DuPont made first film on a polyester base that was more flexible and had other desirable properties. *Kodak*introduced a rapid process (90 second) film development system

1970s

This will probably go down in history as the second most significant decade in the development of screen-film radiography. Being second to the 1890s when it all began. It was the transition from calcium tungstate to rare earth intensifying screens with several related innovations. *Kodak*introduced ultraviolet emitting screens which reduced light crossover. *3M* entered the radiography market with the Introduction of rare earth screens and low crossover film. A high-detail intensifying screen and a single emulsion film designed specifically for mammography was introduced. This began the transition of breast imaging from film exposed directly by x-radiation and a significant decrease in radiation dose to the patient.

1980s

With most of the industry now converted to rare earth intensifying screens there were some continuing developments to enhance image quality. Special emphasis was given to reducing light crossover through the film base that reduced image detail. Methods included a tabular (flat) grain replacing the more cubic grain in the emulsion and designing base materials with increased absorption of the light spectrum, especially in the ultraviolet, emitted by the screens.

During this decade radiography receptors using digital technology began to replace film using the chemical photographic process. It was the beginning of the end of the era in which radiography developed as a major medical procedure by extending conventional film-based photography to visualize the interior of the human body.

A. Acknowledgment

The history of x-ray imaging has been researched and documented by many and their contributions are referenced in the following bibliography. Special recognition is extended to friend and medical physics colleague, Arthur G. Haus. In addition to his career contributions to the development and application of radiographic receptors, especially film, his extensive research on the history of x-ray imaging is published as indicated in the review articles below and provided valuable resources for this manuscript..

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These publications provide extensive information and details on the scientific and technical development of radiography and related clinical applications, especially for the long era when film was used for both the receptor recording medium and display for viewing. Each publication generally gives emphasis to a specific perspective of the historical development and provides a comprehensive coverage. To guide additional reading and research the publications are organized in specific categories. These are Roentgen's Research, History Books, Historical Review Articles, and Research Reports on Specific Developments and Applications.

Roentgen's Research

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