THE SCIENTIFIC AND TECHNOLOGICAL DEVELOPMENTS IN MAMMOGRAPHY
A CONTINUING QUEST FOR VISIBILITY

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Abstract— **The human breast, unlike most other anatomical regions of the body, is composed of normal and pathologic tissues with very small differences in physical density as a source of contrast for x-ray imaging. This low physical contrast cannot be adequately imaged with conventional radiographic methods. Small calcifications, a physical sign associated with some cancers, are also not visible because of the normal blurring within the radiographic process. Effective mammography, *breast radiography*, requires an imaging procedure with high contrast sensitivity to visualize the soft tissue structures and low blurring to enhance visibility of calcifications. The development of this capability has been an ongoing effort for over a half century. Along with developments for increased visibility within the breast there has been progress in optimizing image quality with respect to radiation dose to patients and improving the efficiency of the total mammography process. Transitioning from conventional radiography to mammography required innovations and developments in two specific areas, the x-ray beam *spectrum* and the imaging *receptor*. An x-ray spectrum that was more optimum for mammography used specific anode materials, molybdenum and rhodium and filters of the same elements. The two major requirements for the image receptor that required years of ongoing development were a wide latitude/dynamic range to capture and display contrast, and very low blurring to provide visibility of the small calcifications. After the initial development of mammography using industrial radiographic film exposed directly with the x-radiation, intensifying screens specific for mammography were developed. This was along with developments of film and film processing to be used with the intensifying screens. This development transitioned through several phases including the transition from calcium tungstate to rare earth screen materials and film requiring viewing conditions different from conventional radiography. X-ray tubes with small focal spots were in the dedicated systems developed specifically for mammography. This included a very small focal spot used with geometric magnification to decrease the effective receptor blur and provide the highest visibility of detail of any medical imaging procedure to enhance the visibility of the small calcifications. The approaches to and methods for re-shaping or compressing the breast during the imaging procedure evolved over time. In general, the first half-century of developments in mammography, the subject of this article, used film as a receptor component, archive medium, and display. The development of digital imaging technology provides solutions to some of the challenges in mammography technology and procedures and brings that phase of mammography technology to a conclusion.**

Keywords— **Mammography, breast cancer, image quality, x-ray spectrum, film.**

CONTENT

I. INTRODUCTION

Mammography**,** radiography of the breast, is a major medical procedure for detecting, diagnosing, and managing the treatment of cancer and other breast pathologies. What might appear to be a relatively simple x-ray procedure is in reality a complex process that has faced many challenges in its development over the years. Mammography has a significant and interesting history that has been well researched and documented by others. These authors have focused on diverse topics that define the continuing development of mammography including: clinical applications, professional practice and accreditation, extensive quality assurance activities, political and regulatory requirements, issues in public media, and the highly-significant contributions in the fields of *physics* and developments in *technology*. Our specific interest here is on the physics and technology. Much of this history has been published and is included in the bibliography and addendum at the conclusion of this article and will not be duplicated here. Those articles on the history provide extensive references to publications reporting the research and developments that have resulted in the continuing evolution of mammography. In this article our focus is more on the "why" rather than the just "what" was done in the continuing development of mammography, looking from a physics and technology perspective. This is consistent with the experience of the author, who as a physicist has been involved in the development and clinical applications of mammography for most of its active history.

This focus can almost be summarized in one phrase, the *quest for visibility*. The purpose of a mammography procedure is to provide physicians with the ability to see, or visualize, the internal anatomical structures and potential signs of pathology, especially cancer, within a breast. Here is the challenge. The breast, unlike most of the other regions of human body, is composed of soft tissue with very small differences in physical density that are the source of contrast for imaging. Also, a significant signs of some breast cancers are very small "micro" calcifications that are beyond the visibility of detail capability of most medical imaging methods.

To meet these challenges an effective mammographic procedure must have high *contrast sensitivity* to visualize the soft tissues, including cancers, and extremely *low blurring* for imaging the small calcifications. There is also the goal of minimizing radiation exposure and dose to the patient but with the recognition of the conflicting relationship between image quality and radiation exposure.

A major advancement was the transition from using conventional x-ray equipment to the development of *dedicated* machines specific for mammography.

It was these requirements that defined the continuing development of mammography technology and physics applications that we will now explore.

We begin with an overview of the mammography process in Figure 1.

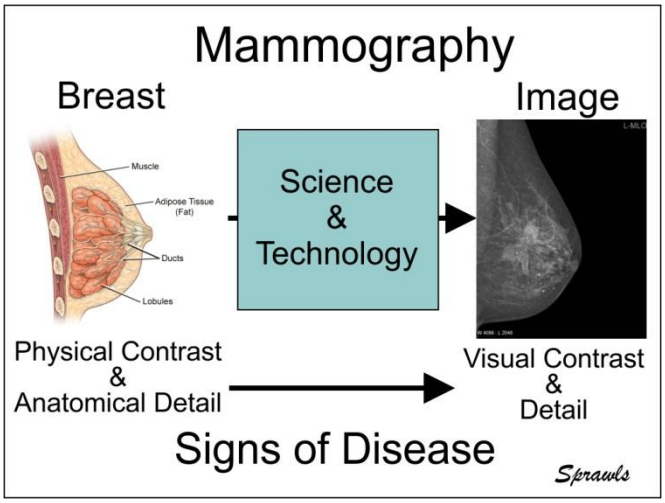

Figure 1. Mammography is based on the application of science, especially physics, and continuing developments in technology, to provide high-quality visualization of the interior of the human breast anatomical structures and signs of disease within a breast.

II. THE EVOLVING ELEMENTS OF MAMMOGRAPHY PHYSICS AND TECHNOLOGY

Mammography is a radiographic procedure. Radiography has been used for imaging most anatomical regions of the human body following Roentgen's discovery and extensive research in 1875. Most of the body, and especially with the

introduction of barium and iodine contrast media, could be imaged with x-radiation. The breast was an exception. There were efforts to do mammography with the available radiographic methods but with limited clinical results. What were needed were modifications of virtually every component of the radiographic system to enable imaging with both high contrast sensitivity and very low blurring. Figure 2 shows the elements of a mammographic system that have been researched and developed in the continuing evolution of mammography.

The two major elements in mammography that are very different compared to general radiography for all other parts of the body, are the *x-ray beam spectrum* and the *receptor and image display*. It is the continuing research and development to improve and optimize these two components of the mammography system that form much of the history that we will now explore.

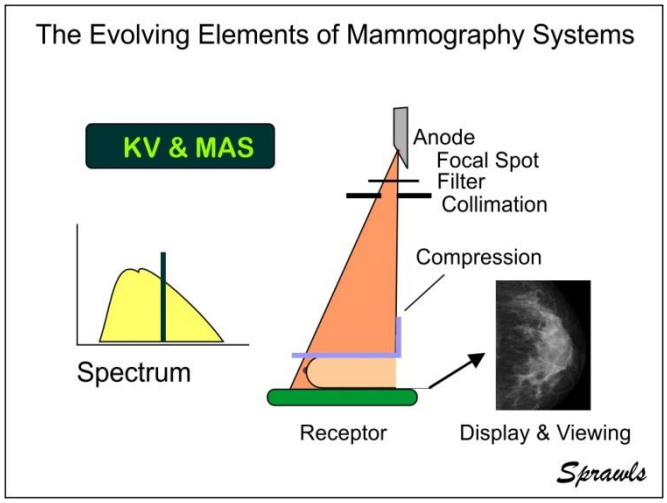

Figure 2. The elements of the mammography system that have evolved over the years in the effort to provide better visualization within the breast.

The evolution of mammography into a highly-effective method for diagnosing and reducing deaths from breast cancer is not just the development of equipment. It was a collaborative effort including extensive clinical research, development of methods and procedures, demonstration of its effectiveness and value, promotion within the medical profession, and major educational efforts. It is these combined efforts by Robert Egan, M.D. that resulted in his recognition as "The Father of Mammography" and provided the foundation for the continuing developments in mammography.

III. THE EGAN METHOD

Dr. Egan joined the faculty of Emory University in Atlanta in 1965, coming from the M.D. Anderson Cancer Center in Houston where he began his pioneering work in mammography while he was in his residency training. It was at Emory where the author of this article, along with several other physicists, were his collaborators in research, continuing development, and clinical applications of innovations in mammography. The so-called Egan Method included the development of an x-ray imaging system specific for mammography along with the development of imaging procedures and techniques. These, along with extensive descriptions of the clinical characteristics and diagnosis of breast cancer, were described in textbooks he authored both for physicians and technologists shown in Figure 3.

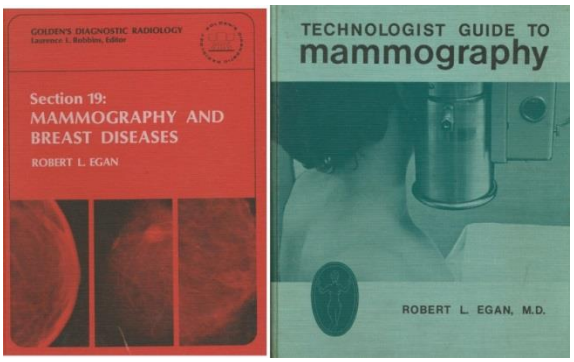

Figure 3. Two of the books by Egan describing the clinical and technical procedures in mammography.

It was these books along with courses by Egan that were a major factor in establishing mammography as a major and valuable medical procedure.

We will now consider the imaging technology and process developed by Egan and collaborating physicists and use it as a reference for the continuing evolution and advances of mammography.

The mammography system can be considered as three major elements that have evolved over the years in the quest of increased visibility and image quality. These are:

- Geometry, Spatial Relationships, and Configuration of the Breast
- The X-Ray Spectrum, Contrast Sensitivity and Radiation Dose
- Image Receptor, Processing, and Viewing

IV. GEOMETRY, SPATIAL RELATIONSHIPS, AND CONFIGURATION OF THE BREAST

This has been one of the major factors that have evolved in the continuing development of mammography technology, especially with the move from the use of conventional radiography to *dedicated* mammography systems. The development of dedicated mammography systems addressed all of the elements listed above with the goal of improving image quality and capability for positioning and obtaining views in clinical procedures.

In The Beginning

The geometry and positing in the Egan method is shown in Figure 4.

Figure 4. The positioning developed by Egan provided three anatomical views considered necessary to properly visualize features and potential cancers within the breast as shown here in his textbook.

The Egan method illustrated here was using modified conventional x-ray equipment. The relatively long x-ray tube to receptor distance reduced focal spot blurring to enhance the visibility of calcifications. What is prominent here, especially from a more recent perspective, is there is no compression of the breast. That develops later.

The Evolution of Breast Compression

The natural shape of the non-confined breast as illustrated in Figure 5 presents a challenge to maximum image quality in several ways.

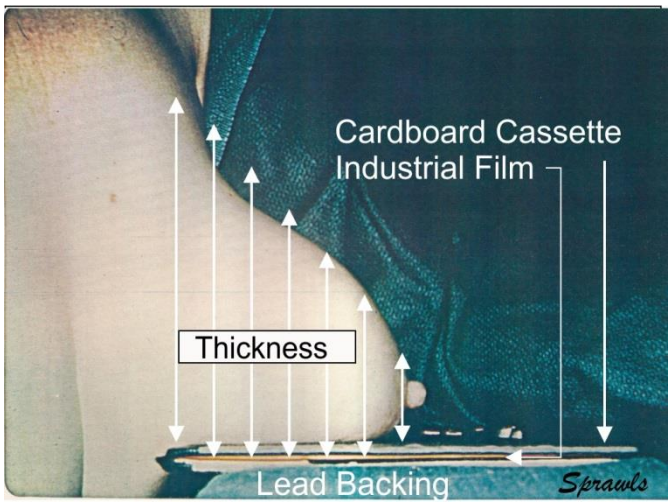

Figure 5. An early mammography receptor consisting of industrial type radiographic film in a cardboard cassette with a lead backing to reduce scattered radiation from the support. Also illustrating the wide range of breast thickness to be imaged in this photograph by the author.

The variation in thickness from the chest wall to the nipple creates a wide range of exposures to the receptor that can extend beyond the latitude/dynamic range of film and result in reduced contrast as will be discussed later.

Adequate visualization of micro calcifications requires the total blurring to be limited to approximately 0.15 mm. Exposure times in mammography can be several seconds, very long compared to most other radiographic procedures. Almost any patient motion during the exposure can be detrimental to image quality.

Physical compression and stabilization of the breast was developed to improve image quality both with respect to contrast and reduced blurring. The general evolution of compression is illustrated in Figure 6.

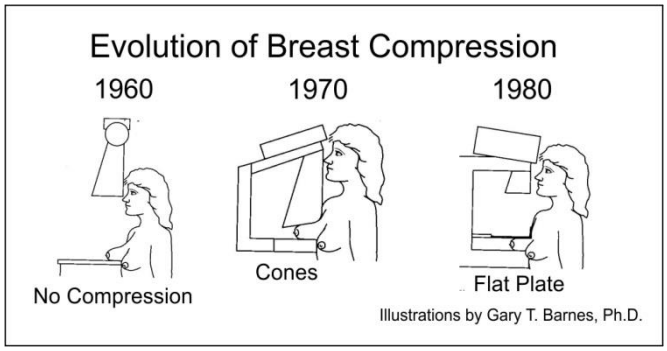

Figure 6. The three major phases of imaging geometry and breast compression.

A continuing challenge to breast compression, especially very firm compression, is discomfort to the patient. In the 1960s, when conventional x-ray tubes with tungsten anodes were used, the x-radiation was generally more penetrating than with the later molybdenum anode and filters. When using the directly exposed film developed for industrial radiography the latitude or dynamic range issue appeared to be less of a problem, so compression was not considered necessary for adequate quality.

After that, and as x-ray systems were developed specific for mammography, some type of compression and breast stabilization was included by the x-ray beam cone and sometimes with soft components in contact with the breast.

The introduction and continuing development of flat plate compression illustrated in Figure 7 was a major contribution to image quality in several ways.

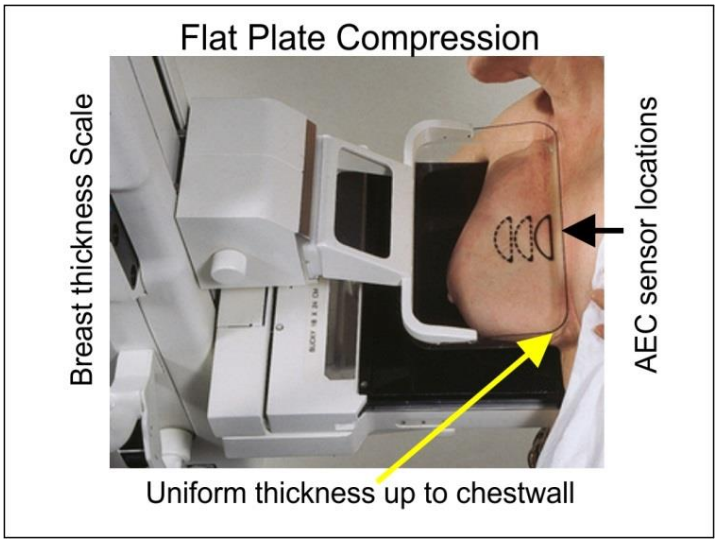

Figure 7. Features associated with flat plate breast compression devices that contribute to improved image quality are identified in this illustration provided by the author.

The stabilization of the breast that eliminated most patient motion reduced that potential source of blurring and enhanced visibility of calcifications. However, the major contribution is the re-shaping of the breast into a more uniform thickness spread over a slightly larger area. The uniform thickness reduced the range of x-ray exposure to the receptor and loss of contrast because of film latitude limitations. The spreading of the breast tissue, especially in the thicker regions, reduced the overlapping of objects and structures that could potentially interfere with visualization. This was especially significant for imaging the tissues up to the chest wall.

There are several other features in the development of the compression system that aided the technologist in producing high-quality images. One was the measurement and display of the compressed breast thickness that was a major factor in selecting optimum technique factors. Also, the diagram on the compression plate guided the selection of the appropriate automatic exposure control (AEC) sensor location for each specific patient procedure. The sensors were located below the receptor so that they did not interfere with the image. By selecting which sensor location to use the technologist determined the area in the breast that would result in the desired film density.

The evolution of breast compression is a significant element in the history of mammography. It has focused on modifying the anatomical environment of the breast for optimum imaging. In spite of its contribution to high-quality imaging, the compression technique is a source of discomfort and pain to patients. The challenge continues.

V. THE X-RAY SPECTRUM, CONTRAST SENSITIVITY AND RADIATION DOSE

The production of a visible image depends on the ability to "see" physical contrast within the body and convert that into visible contrast within an image. Physical contrast is the difference in *physical density* among the tissues and body structures with some contribution from differences in atomic number (Z). The bones within the body were the first to be imaged (beginning with Mrs. Roentgen's hand) because of the high physical contrast between the calcium in the bones and the soft tissues in the body. It was soon discovered that the chest could be imaged because the low-density air within the lungs provided an excellent background for the more dense bones, fluid, and signs of disease within the lungs. With the development of contrast agents containing barium and iodine with their desirable atomic numbers for x-ray attenuation, the scope of imaging, both radiography and fluoroscopy, was expanded to include virtually all regions and systems of the body, *except for the breast.*

The Challenge of Breast Imaging

X-ray imaging of the breast—mammography—faced many challenges and required many years of research and development to reach its full potential. The major factor is that the breast is composed of soft tissues with small differences in density and physical contrast both among the normal anatomical structures and abnormal tissues, especially cancers. The visualization of these requires a procedure with higher *contrast sensitivity* than more conventional radiographic procedures.

The physics of x-ray image formation was well established with the known dependency of x-ray attenuation, specifically the photoelectric effect, and the formation of contrast among low atomic number soft tissues inversely related to photon energies. An x-ray spectrum with low photon energies would be required to produce adequate contrast and visibility among the soft tissues, both normal and pathologic tissues including cancer. There was also the factor that the lower photon energies were less penetrating through the total breast and resulted in increased exposure and dose to the breast. Both of these factors, image contrast and dose, also depended on the thickness and density of the breast. This was to be a major challenge to be addressed throughout much of the development of mammography with two questions:

- What is the optimum spectrum for imaging a specific breast size?
- How to produce an x-ray beam with that spectrum?

The Optimum X-ray Spectrum

That question began to be answered by Gajewski, H & H Reiss, K. Physical fundamentals and technique in soft tissue diagnosis. Der Radiologe. 14. 438-46. (1974). With their innovative research and results shown in Figure 8.

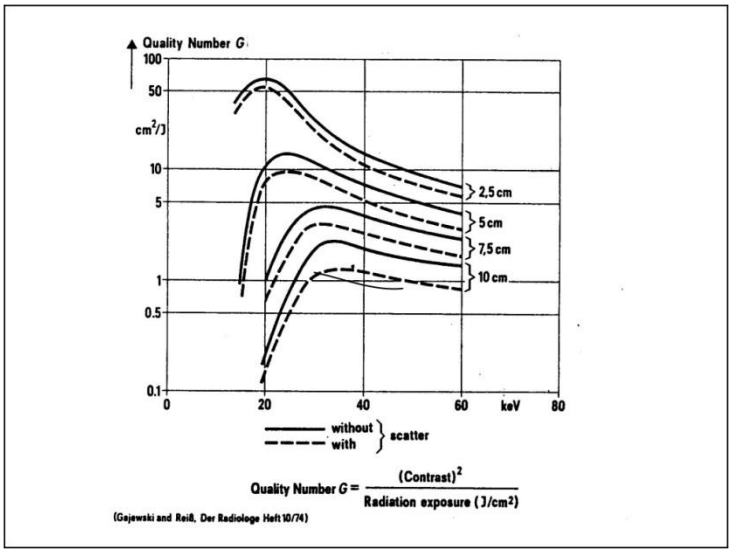

Figure 8. A quality number representing the ratio of contrast to dose displayed over a range of photon energies.

These experiments conducted with varying thicknesses of water simulating a range of breast sizes with measurements over a spectrum up to 60 keV demonstrated several factors that were to guide the developments in mammography for many years to come. Perhaps the most significant was optimum photon energy for specific breast sizes and that it increased with size. Also, as breast size increased, the ratio of quality to exposure decreased, with scattered radiation becoming a more significant factor.

This demonstrated that for the expected range of breast sizes, especially when compressed, of 2.5 mm to 7.5mm, the optimum photon energy was in the range of 20 keV to 30 keV. The challenge was how to produce x-ray spectra to fulfill these requirements. A reasonable assumption is that an x-ray machine that produces a mono-energy spectrum that could be adjusted with respect to breast thickness and density would be the "ideal" system. However, that is yet to be developed.

In principle, the x-ray spectrum should be adjusted to be *optimum* for each patient in relation to breast thickness and density. For many years the anode and filter materials were determined by the design and construction of the equipment and could not be changed by the operator, leaving KV as the adjustable technique factor.

Tungsten and Minimum Filtration

In the beginning x-ray tubes with tungsten anodes were available and used for all medical imaging procedures. The imaging system developed by Egan and his physics team consisted of conventional tungsten anode x-ray tubes with the added filter removed leaving only inherent tube window material.

X-ray tubes with beryllium windows were becoming available and used in mammography. Beryllium has an atomic number of 4 and a relatively low density (1.85 g/cm3) minimizing its x-ray attenuation, especially for the lower-energy photons. In some applications beryllium window tubes were used without additional filtration but with concern for high exposures to the breast. The ultimate advantage of beryllium window tubes was permitting other types of filters to be added that were more appropriate for breast imaging, as described later.

At this time mammography was performed with film as the receptor exposed directly with x-radiation without intensifying screens to minimize blur. This required a relatively high x-ray exposure. In addition to producing radiation over a long exposure time, up to 6 seconds, a major requirement for the modified equipment was the capability of providing low, adjustable, and accurate KV values over the range of 22 kV to 34 k V.

In addition to modifying the x-ray tubes with respect to filtration the generators or power supplies require some changes in design. For effective mammography they were required to operate at lower KV values than for conventional radiography and with good accuracy and produce high tube currents, MA, over a relatively long exposure time. Initial experiments have used modification of some existing X-ray equipment used for radiography (50 to 120 kV), grounding one side of the high voltage generator, thus producing half of the kV range (25 to 60 kV), using the existing kV regulation of the generator.

Typical Egan technique factors for a medium size breast was 28 kV, 300 mA, 6 seconds (1800 mAs), and a FRD of 36 in.

Figure 9 shows physicists in Egan's laboratory at Emory University analyzing the performance of the x-ray generators being developed for mammography.

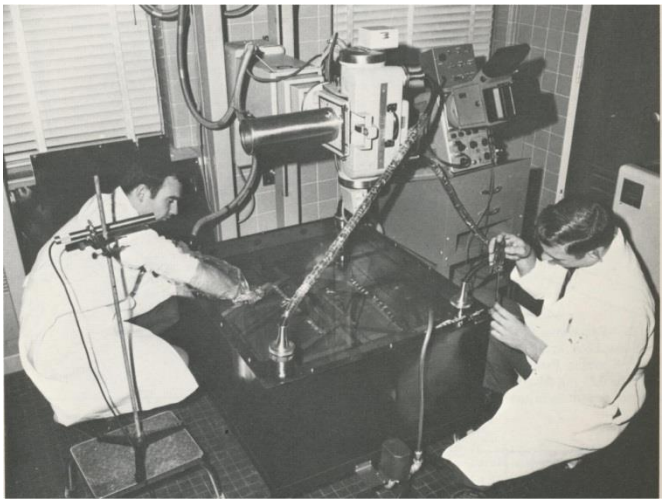

Figure 9. Physicists using a bank of resistors in a tank of insulating oil as an electrical load to evaluate the performance of x-ray generators being developed for mammography

The Significance of KV on Procedure Optimization: Image Quality and Radiation Dose

Conventional radiography equipment, especially with modifications as described, played a role in establishing mammography as a valuable medical procedure. However, limitations were realized. One of these was the necessity to have accurate and precisely controlled KV values in the general range from 24 kV to 34 kV. The KV value was to become the major adjustable technique factor by the technologists in relationship to the thickness and density of individual patient breasts. Differences in KV values as little as 2 kV were significant in optimizing a procedure with respect to quality and dose.

The inclusion of generators/power supplies that could meet these KV requirements was one of the major features of the *dedicated* mammography systems to be developed. Also, measuring and evaluating KV accuracy became a required quality assurance function performed by medical physicists.

The Impact of Molybdenum: Anode and Filters

Molybdenum is a metal with a high melting point and an atomic number (Z) of 42. It is the combination of these two characteristics, especially the atomic number that has made molybdenum a major element in mammography both as an x-ray tube anode material and x-ray beam filter. When used together the x-ray spectrum shown in Figure 10 is produced.

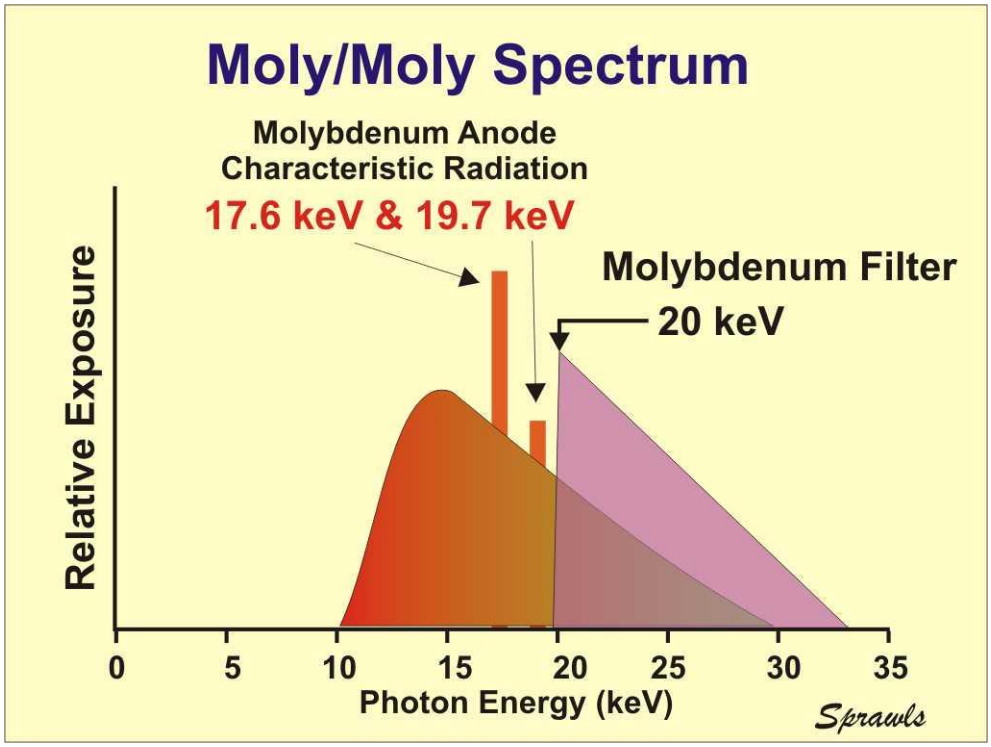

Figure 10. The x-ray spectrum produced with the combination of a molybdenum anode and filter.

The significant characteristic of molybdenum with its atomic number (Z) of 42 is that the anode produces characteristic x-ray peaks at 17.6 keV and 19.7 keV and a filter attenuation K edge at 20 keV as shown. It was with this introduction that *characteristic radiation*, and not bremsstrahlung, became a major component of mammography.

It is the combination of the molybdenum anode and filter that produces an x-ray spectrum within a relatively narrow range of energies near 20 keV that makes it optimum with respect to image contrast and radiation dose to patients, especially for smaller breasts as indicated in Figure 8.

The molybdenum anode and filter was, and continues, to be the foundation of x-ray breast imaging. Some developments described later shifted the spectrum to slightly higher energies that were more optimized for larger and denser breasts.

Moving Up to Rhodium

It was recognized that the molybdenum – molybdenum (anode and filter) aka "moly-moly" spectrum, while appropriate for smaller breasts, was not optimum for all. A solution was provided by the element rhodium. It has some of the same metallic properties as molybdenum, including a high melting point. However, its atomic number (Z) of 45, compared to 42 for molybdenum, shifts both the characteristic radiation and the K-edge energies up to higher values. This is optimum for larger and denser breasts. This spectrum is shown in Figure 11.

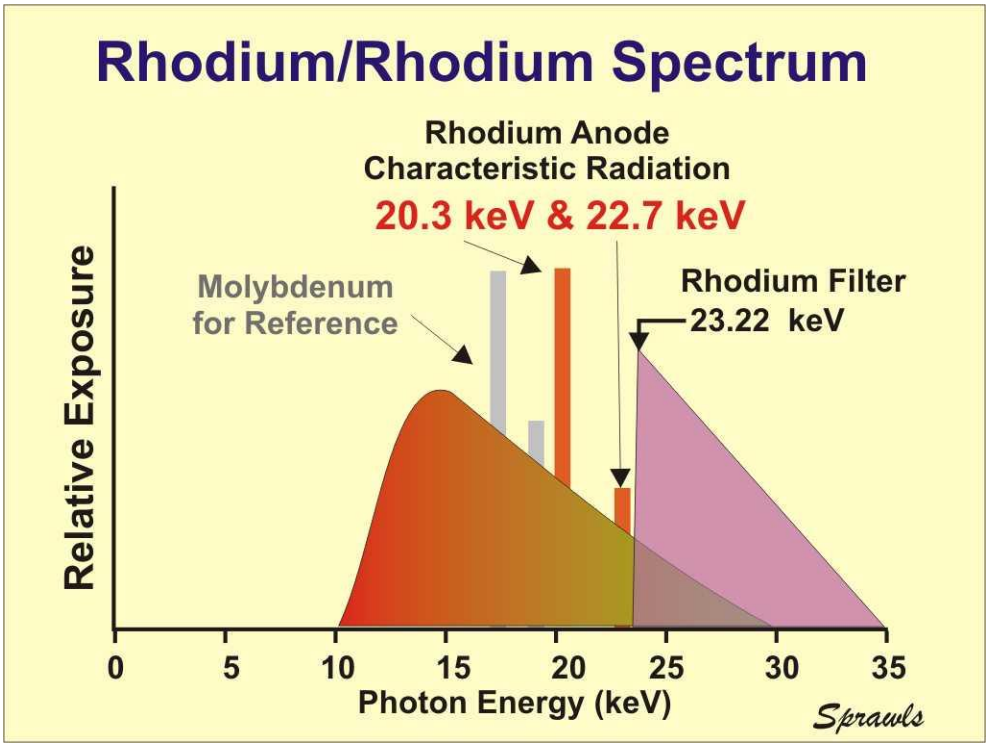

Figure 11. The spectrum produced with a rhodium anode and filter.

The advantage of rhodium over molybdenum was higher photon energy and a more penetrating x-ray beam. This had the effect of reducing doses to patients and potentially better visualization through some denser breast tissues. This was developed and applied in two phases, the filter and the anode.

A rhodium filter is a relatively simple small metal object that can be added as an alternative filter to the many systems with molybdenum anodes. It can then be used with the molybdenum anode tubes to increase penetration by passing the *bremsstrahlung* between the energies of 20 keV and 23.22 keV, the differences between the two K edges.

In 1992 General Electric introduced a dual track x-ray tube with a molybdenum anode track, molybdenum filter, a rhodium anode track, and a rhodium filter. The operator could select the function to produce either the spectrum shown in Figures 10 or 11, depending on the characteristics of the breast being imaged.

VI. DR. CHARLES MARIE GROS, SENOLOGY, AND THE SENOGRAPH

Dr. Charles Marie Gros was a physician and physicist serving as Professor of Medicine from 1950 – 1975, and Head of the Department of Radiotherapy and Radiology at University of Strasbourg, France. In 1963, he created a multidisciplinary medical specialty for the care of breast diseases and established the term *Sénology*. In his landmark publication by that title he defined senology (the study of the breast) as a neologism derived from the Romanic “seno” and the Greek “logos” as the branch of knowledge concerned with the mamma and the breast.

In 1975 he founded the Société Internationale de Sénologie (SIS) and published the first Journal on Breast Diseases: *Senologia*.

He developed the first equipment exclusively dedicated to breast imaging and collaborated with the Compagnie Générale de Radiologie (CGR), in developing and promotion of the mammography equipment called the Senograph shown in Figure 12.

Figure 12. The contributions by Dr. Gros included the formation of a society and journal and the development of the first dedicated breast imaging system, the Senograph.

VII. THE TRANSITION TO DEDICATED MAMMOGRAPHY SYSTEMS

In 1965 the Senograph developed through the efforts of Dr. Gros in collaboration with "Compagnie Générale de Radiologie (CGR)" became the first dedicated breast imaging system. One of its major features was using molybdenum for the anode and filter.

It is reported that by 1970 CGR had sold approximately 2000 Senographs throughout the world. Later General Electric purchased CGR and continued with Senography as the brand name for its dedicated breast imaging systems.

Other manufactures developed dedicated systems. These include the Mammomat by Siemens, MicroDose by Philips, and several brands by Hologic. Each of these could have included some special features but also the common features optimizing them for breast imaging including:

- Low and Adjustable KV
- Molybdenum Anode and Filters
- Grids with Low Attenuating Interspaces at the Low Photon Energies
- Dual Small Focal Spots
- Ability to Rotate for Different Anatomical Views
- Breast Compression and Positioning Capability
- Automatic Exposure Control Selectable by Operator

Before the transition to digital, the receptors were not provided by the equipment manufactures but by the major film industry including: Kodak, DuPont, Fuji, and Agfa. With the exception of xerography as described later, there were two major receptor components, *film* and *intensifying screens*. Each of these progressed through extensive developments contributing to improved image quality and controlling radiation dose to patients.

VIII. THE EVOLUTION OF FILM AS A MAMMOGRAPHY RECEPTOR

The special image quality requirements for mammography, especially high contrast sensitivity and visibility of detail, could not be provided with conventional radiography receptors. Receptors specific for mammography have been developed and have evolved throughout history. There are several desirable receptor characteristics that have motivated and guided the continuing innovations and development over the years.

Contrast Sensitivity and Dynamic Range

The transfer of relatively low physical contrast (differences in tissue densities) to visible contrast in images is one of the major challenges in mammography. This is determined by the contrast sensitivity of the imaging system. The first step in meeting this is through the optimized x-ray spectrum that has been described. When the invisible x-ray image from the

breast is delivered to the image receptor there continue to be several factors that determine the contrast that will be visible in the final image.

A related factor is the range of x-ray exposure to the receptor over which contrast will be produced. This characteristic is the *latitude* for film and *dynamic range* for digital receptors. There is generally a conflict between high visual contrast and latitude. This has resulted in the design of film specific for mammography and the necessity of special viewing conditions to be used by physicians.

Film with Direct X-ray Exposure

When mammography was being developed general radiography for all other parts of the body was being conducted with film exposed in cassettes with intensifying screens. This was not satisfactory for mammography for two major reasons. The blurring from the intensifying screens did not provide the adequate visualization of the small calcifications, and the film latitude (dynamic range) could not produce the necessary contrast over the wide range of receptor exposure caused by the variation in breast thickness. These two limitations were overcome by using film exposed without intensifying screens. The first mammographic receptors developed by Egan were film exposed directly by the x-radiation without intensifying screens as illustrated in Figure 5. The preparation of the film for imaging is shown in Figure 13.

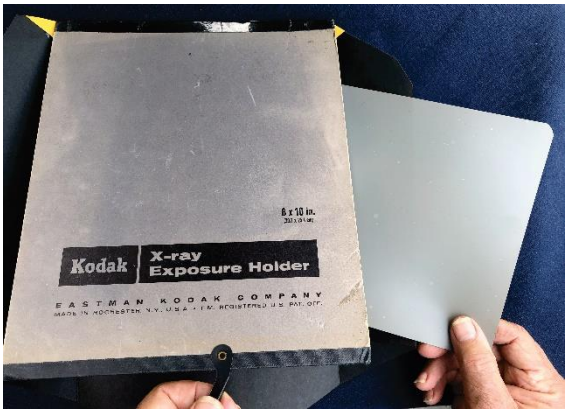

Figure 13. Industrial type film being inserted into a cardboard holder to be used as a receptor for mammography.

A specific type of film selected by Egan was Kodak Type M designed for industrial radiography. It had fine-grain, high density, and a thick emulsion. The thick emulsion required longer processing times than conventional radiographic film of the time. This was provided with either modified film processors or manual processing as shown in figure 15. The manual processing was recommended for maximum image quality.

Future developments in film and intensifying screen technology led to the replacement of directly exposed industrial film with intensifying screen-film combinations designed specifically for mammography. This occurred in two major phases and the film characteristics for each are compared in Figure 14.

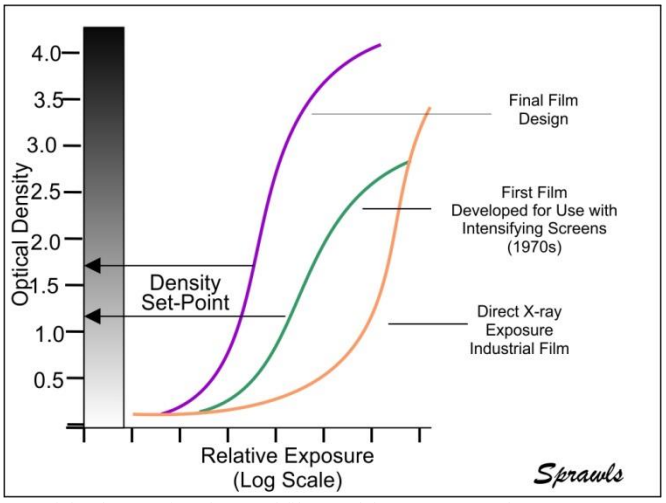

Figure 14. Characteristic (H & D) curves of the three major phases of film used for mammography.

This illustration compares the features of each type beginning with the directly exposed film. A major difference between films exposed with x-radiation and light is that with light exposure there is a limited maximum optical density that can be achieved resulting in the shoulder on the characteristic curve. With the direct x-ray exposed films to obtain the wide latitude required long chemical development times and manual or hand processing. With some of the image contrast recorded in the high-density or dark regions of the film special bright lights were required for viewing. These two characteristics are illustrated in Figure 15.

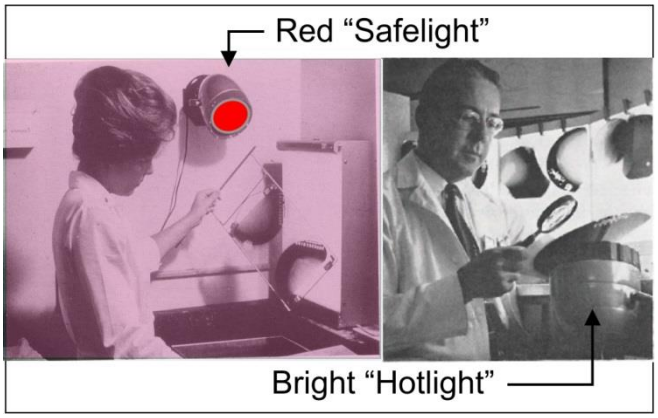

Figure 15. The manual processing of mammography film and Dr. Egan viewing the high-density areas with a bright "hot" light at Emory University.

Automatic film processors were used for general radiography but were not adequate for processing the industrial type film used in mammography. This film had a thicker emulsion and required longer times in the developer solution to convert all of the exposed grains to opaque optical density. The film was not sensitive to the red region of the light spectrum and the darkroom could be illuminated with a red "safelight" to provide visibility of the process. It required considerable experience and skill to work with the many variables associated with the process.

This was the beginning of the necessity to view mammography images with a bright light because of the extended density (opaqueness) into the darker range to provide the wide latitude/dynamic range, especially needed because of the variation in breast thickness as illustrated in Figure 8. The necessity for special "bright light" viewing returned as an issue years later with the design of the film for mammography that had extended latitude into the more dense (opaque) regions as illustrated in Figure 14 for the final film design.

Direct X-ray Exposed Film Summary

The directly-exposed industrial type film as a receptor for mammography was a major factor in the development and evolution of modern mammography. The ability to produce images with high visibility of detail (calcifications) and adequate contrast over a wide exposure range made effective clinical mammography possible, especially with the Egan Technique. One of the several challenges was that the manual processing of the film required considerable effort.

The characteristic that was the major concern and driving force for the development of other receptors was the high x-ray exposure required to form images when the film was exposed directly by the x-radiation.

This motivated the development of intensifying screen – film combinations for mammography. This generally occurred in two phases relating to developments of intensifying screens for all radiographic procedures. Films with specific characteristics to be used with each type of intensifying screen were developed. It is the film within the receptor that determines the contrast characteristics of an image and the contrast sensitivity of the imaging procedure. Before considering the intensifying screens we follow the evolution of film characteristics, and impact on visibility using the illustration in Figure 14.

Film Used With Intensifying Screens

A general characteristic of film exposed with light, compared to direct x-ray exposure, is a lower limit to the maximum optical density, or opaqueness that can be achieved. This has an impact on image contrast and especially the range of exposure (latitude or dynamic range) over which adequate contrast and visibility can be developed. A major factor relating to variations in breast thickness was described previously.

The receptors for mammography with intensifying screens used one screen rather than the two screens used for most other radiographic applications. This was to reduce image blurring as will be discussed later. The film had an emulsion on one side of the film base and was used with a single intensifying screen. However, the film emulsion was thicker for the purpose of producing an optical density comparable to films with emulsions on each side. The thicker emulsions generally required longer times for the chemical development to reach completion and special automatic processors with extended processing times were sometimes used.

The contrast characteristics of these earlier mammography films were not extensively different from film for other radiographic procedures. The films were exposed to produce approximately same range of densities as other radiographs and viewed under similar conditions.

The third and final phase of film-based mammography receptors resulted from innovations in both the intensifying screens, to be described later, and the film described now. The contrast characteristics associated with these three phases are compared in Figure 14 and will be used here as a reference.

A continuing objective in film design was to provide necessary image contrast over a wide range of exposure to the receptor--that is, wider latitude or dynamic range. With radiographic film one factor that limits latitude is the maximum optical density that can be produced. The specific characteristic that contributed to the wider useful latitude is the film emulsion design that can produce higher optical densities, or so called " D_{max}".

To benefit from this film design required two changes in practice. First, the images needed to be exposed to a higher average optical density to fall within the wider latitude. The automatic exposure control was calibrated for a density set point of approximately 1.7 compared to approximately 1.2 for the earlier film types as illustrated in Figure 14. This was the film density that resulted from exposing a phantom test object of uniform thickness representing an average breast. The second factor was that the denser or darker images required different and special viewing conditions.

Mammography Film Viewing

The viewing conditions for mammograms recorded on the two film types are compared in Figure 16.

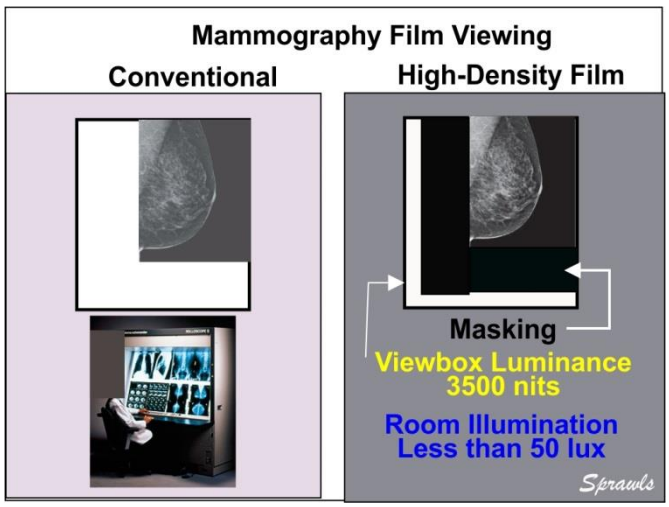

Figure 16. Comparison of the viewing conditions for the two general types of mammographic films.

For years the mammography film used with intensifying screens produced approximately the same optical density images as other radiographs and was viewed under the same conditions illustrated above. However, with the development of film producing images with greater optical density (opaqueness) the conventional viewing conditions were not adequate. The human visual process could not see all of the contrast and details in the darker images, and especially with surrounding glare and bright viewing rooms.

This was overcome with viewing conditions specific for mammography with three features. This included brighter illuminators (view boxes), masking around the small images while viewing, and darker rooms. The specifications, as required by some accrediting and regulatory organizations, are shown in Figure 16.

The Chemical Processing of Film for Mammography

The chemical processing and development of films for mammography had special requirements. For some types of film this was extended development times to achieve increased density and contrast. However, the trend was to design mammography films that could be processed along with other radiographic films in automatic processors that were the standard at the time. A major challenge was that film development was a chemical (not physical) process and subject to many variables including type and quality of the chemistry, replenishment as it was used, and solution temperature. Even in an automatic processor it was potentially an unstable and varying process. What varied was the level of development that determined how many of the exposed silver halide grains (the invisible latent image) were converted to visible density in the final image. This affected both the sensitivity and contrast characteristics of the receptor. The concern with under-developed film was both a loss of contrast and the requirement of higher exposure. Variation in development levels (consistency) could contribute to exposure errors and the necessity of repeating examinations.

Quality Control (QC) procedures specific for mammography film processors became a recommendation and requirement in many countries. These were often under the direction of medical physicists.

IX. XEROMAMMOGRAPHY

The xerography process, from the Greek, *xeros*, "dry" and *graphia*, "writing" was developed and used extensively in equipment for making copies of documents and images. Unlike other methods, including photographic film, it does not use "wet" chemicals but a completely dry electrostatic process to form images. The basic process as used for mammography is illustrated in Figure 19.

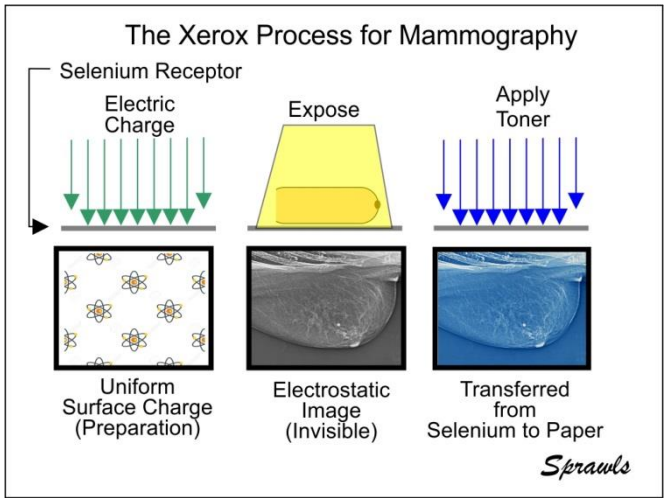

Figure 19. The three major steps in the formation of a Xerox mammogram.

The active component of the receptor is a layer or plate of selenium, an electrical semiconductor, enclosed in a lightproof cassette for imaging.

Preparation

In the first step within the processor the plate is cleaned from previous use and an electrical charge applied to the surface. It is then re-inserted into the lightproof cassette and ready for imaging.

Exposure and Image Formation

When exposed to x-radiation the selenium plate becomes conductive and discharged at each location in proportion to the exposure. This forms an invisible image in the form of a variable electrical charge on the surface of the plate.

Processing and Image Development

The cassette is inserted into the processor where the selenium plate with the electrical charge is sprayed with a fine-grain blue powder or "toner". The powder collects at each point on the surface in relationship to the charge and forms a visible image. It is then pressed onto a sheet of paper transferring the image. With some additional processing and sealing it is expelled from the processor as a permanent printed image.

Characteristics of Electrostatic Images

It was the unique way that electrostatic images, as different from chemical photographic images, are formed that provided several advantages for mammography. A major characteristic is that the attraction of the blue powder toner is most prominent at local transitions or gradients in the electrical charge and less dependent on the actual charge value throughout the larger image area. This produced images with two very valuable characteristics for mammography.

Edge Enhancement and Wide Latitude

A major challenge in breast imaging has been the large variation in breast thickness and density that could extend exposure beyond the latitude or dynamic range of film as described early. Another challenge is the need to image very small calcifications and anatomical detail. The unique characteristics of electrostatic imaging in the xeroradiography process provided solutions to both of these challenges as illustrated in Figure 20.

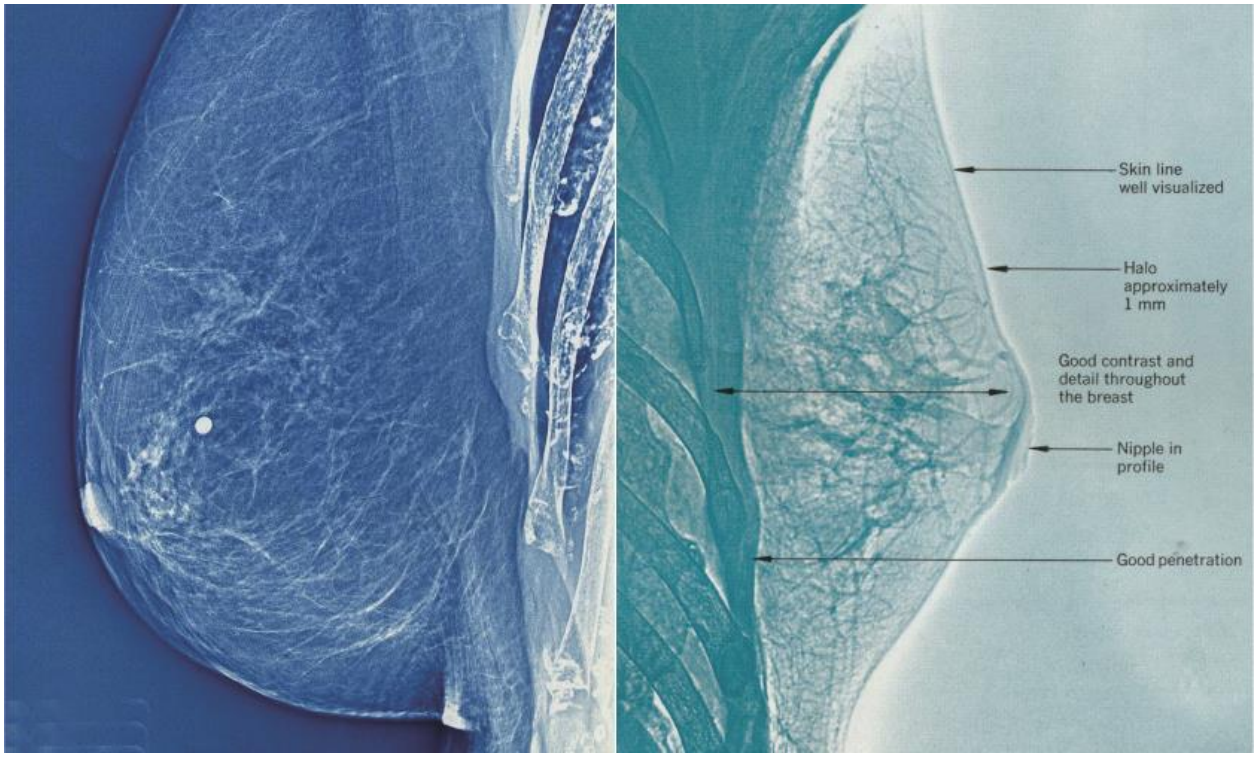

Figure 20. Images of a breast illustrating some of the advantages in technical brochure published by Xerox.

The edge-enhancement characteristic contributes to increased visualization of detail and small objects because they are more in the form of closely spaced edges or boundaries than being large areas.

Xerox for mammography was commercially introduced in 1971 and became a desirable alternative to directly-exposed film, both because of image characteristics and less radiation exposure compared to directly-exposed film. The images were especially appealing to physicians because of enhanced visibility of anatomical structures and the radiation dose was less than with directly exposed film. 1n 1985 black liquid toner was introduced but this did not contribute to the significant continuation of Xerox mammography.

As receptors with intensifying screens (LoDose, MinR, etc.) were developed and becoming widely used in the late 1970s their image quality characteristics and significantly lower radiation dose requirements contributed to the decline of xeromammography with commercial production ending in 1989.

X. THE INTRODUCTION AND EVOLUTION OF INTENSIFYING SCREENS

Mammograms produced with film as the receptor and exposed directly by x-radiation had good quality. The good contrast characteristics and low blurring was a major factor establishing mammography as a highly valuable procedure for diagnosing breast cancer. However, a major concern was the high exposure required to form images. This was a motivation to develop receptors with intensifying screens. Film-screen combinations, either in cassettes or rapid film changers were the receptors used in virtually all radiographic procedures. Even the so-called “detail” screens produced higher blur than was needed to image the small calcifications. The standard design of film-screen receptors used a film with the emulsion on both sides of the film base “sandwiched” between two intensifying screens. With these receptors there were three sources of blurring that limited visibility of detail (including calcifications) and making them not appropriate for mammography. These were 1. The thickness of the screens necessary to provide x-ray attenuation; 2. light crossover through the film base between the two emulsions; and 3.some possible space between the film and screen surfaces because of problems with film-screen contact. It was necessary to address each of these factors in the design and application of intensifying screens for mammography. The characteristics of intensifying screen receptors for mammography are compared to those for general radiography in Figure 21.

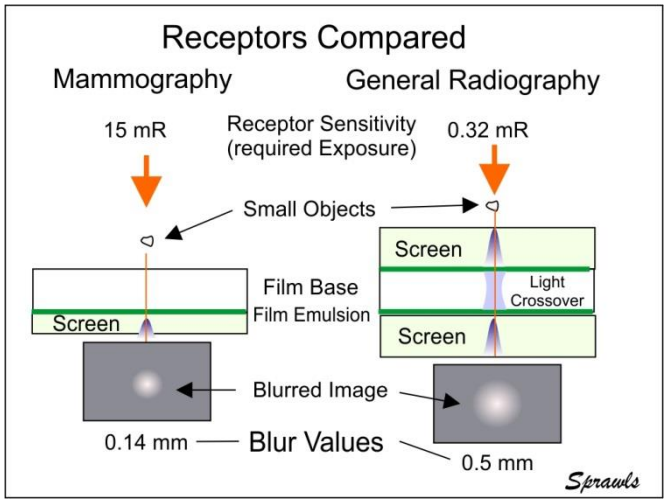

Figure 21. Comparison of intensifying screen receptors for mammography to general radiography.

The delay in using intensifying screens for mammography was the inherent blurring that limited visibility of calcifications and related anatomical detail. The two specific design features to address this was using a thinner screen and only one screen combined with a film that had emulsion on one side…different from conventional radiography that uses two intensifying screens with the emulsion on both sides of the film. Placing a film into a mammography cassette is shown in Figure 22.

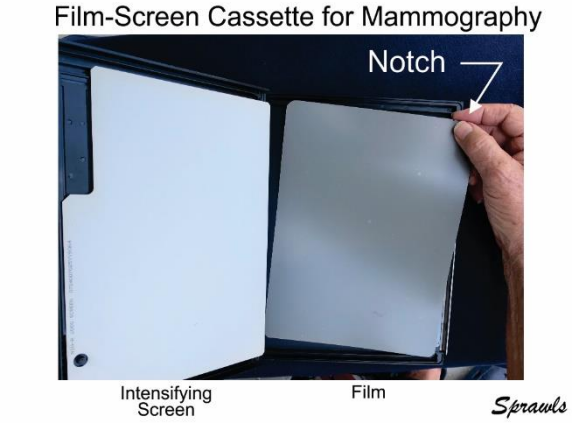

Figure 22, Inserting film into a single screen mammography cassette. This was in a darkroom so there was a notch in the film to identify the upper right corner when viewing the emulsion side.

While the development and transition to intensifying screens for mammography was motivated by the need to reduce radiation dose, the resulting exposure requirements would continue to be much higher than general radiography. In mammography there are two major factors that determine radiation dose to the breast, and both are in conflict with requirements for high image quality. One is the x-ray beam spectrum that should be optimized to balance dose with requirements for high contrast sensitivity, as described previously. The other is the exposure required by the receptor to form an appropriate image where increased exposure is required to reduce both blurring and visual noise.

Receptor Sensitivity (Speed) and Exposure Requirements

Transition from directly exposed film to Xerox mammography and then to intensifying screens provided a reduction in the exposure required to form images. However, the reduction in exposure and dose continued to be limited by image quality requirements, especially the effects of blurring and visual noise. The thin intensifying screen used with a single emulsion film resulted in an equivalent blur value of approximately 0.15 mm compared to values of around 0.5 mm for general radiography receptors. While this low blur value enhanced visibility of detail, specifically small calcifications, it also contributed to increased noise. That is because blurring has the effect of integrating photons within an area and reducing noise. This results in receptor sensitivity (required exposure) values of approximately 15 mR for mammography compared to 0.32 mR for a typical 200 speed general radiography receptor.

The receptor sensitivity values shown in Figure 21 are the input exposures required by receptors to produce a specific reference film density, generally one unit above the base plus fog density. It can be considered as an approximation of the average receptor exposure to form an image.

Because reduction in dose was the major motivation for developing intensifying screens for mammography this was emphasized in the early brand names including LoDose by DuPont and Min-R by Kodak.

In 1972 DuPont introduced the LoDose receptor that consisted of a thin calcium tungstate screen used with a single emulsion film enclosed in a flexible vacuum bag so that the earth's atmosphere pressed the film and screen together for good contact. To prepare for each image the technologist would insert the film into the bag with the intensifying screen and then use a manual vacuum to produce the compression.

In 1976 the rigid cassette was introduced which contained one screen and used with single emulsion film. This included the DuPont LoDose-2 continuing to use calcium tungstate and the Kodak Min-R system using a gadolinium oxysulfide screen. It was at this time that intensifying screens for radiography were transitioning from calcium tungstate that had been used for years to a variety of the rare-earth phosphors including gadolinium oxysulfide. Receptors with generally similar characteristics were provided by several other manufactures.

The evolution from calcium tungstate to the several rare-earth intensifying screens was a major advancement for general radiography. A contributing factor was the difference in atomic numbers (Z) between calcium tungstate and the rare earths. With the lower atomic numbers and K-edge energies the rare earths provided higher x-ray absorption rates within the x-ray spectrum used for general radiography and screen thickness could be reduced. Along with some associated developments the exposure to produce images was reduced. The transition to rare earth screens for mammography provided some reduction in exposure and dose but mammography remains a relatively high exposure procedure as will be discussed more below.

XI. VISUALIZING CALCIFICATIONS

Calcifications are one of the significant signs of some breast cancers. It is not just the presence of calcifications--many are benign--but the size, shape, configuration, and distribution that must be evaluated to diagnose cancer. Calcifications within the breast are generally divided as either *macro* or *micro* with 0.5 mm being a dividing point. It is the micro calcifications with dimensions less than 0.5 mm that are generally associated with cancer.

Test Objects and Phantoms for Visualizing Calcifications

Test objects or phantoms to evaluate the visualization of the small calcifications played a major role in both the development of mammography methods and the continuing quality assurance procedures conducted by medical physicists. Two of the earliest developed by Egan is shown in Figure 23.

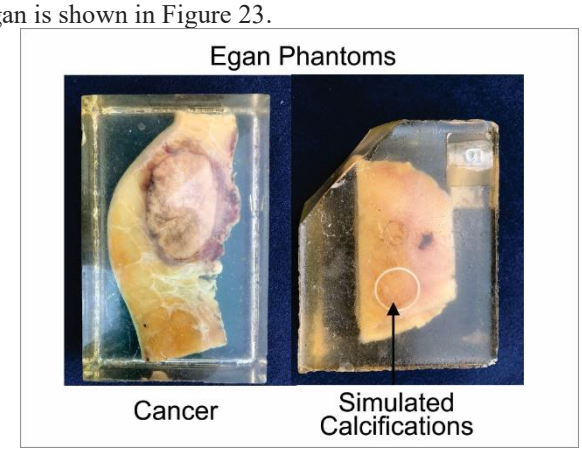

Figure 23. Phantoms developed by Egan to evaluate the contrast characteristics of a cancer and visibility of small calcifications in breast tissue.

The phantom was a section of breast tissue and cancer from surgery and embedded in a plastic block. Simulate calcifications with a range of sizes were added within marked circular areas. The image quality and visualization was evaluated by counting the number of calcifications visible with the circular area.

Over the years as mammography was being developed a variety of phantoms and test patterns were created and used. These included a design that was the standard for the accreditation of mammography facilities by the American College of Radiology (ACR) and various quality assurance procedures. A diagram and image is shown in Figure 24.

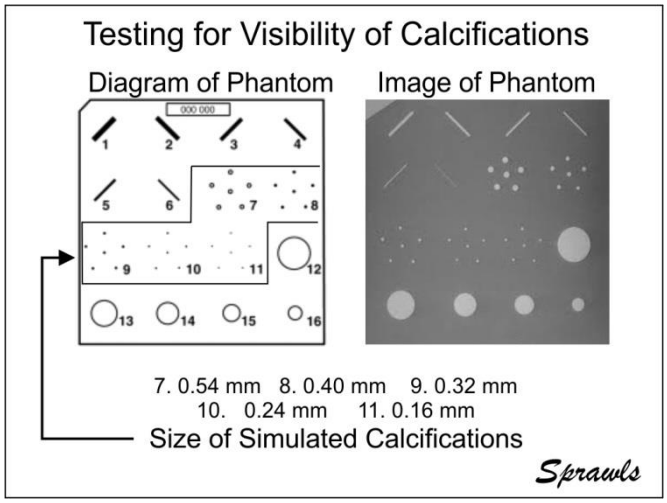

Figure 24. Diagram and image of the breast phantom that became a standard for evaluating mammography equipment performance.

The phantom was used to evaluate general contrast sensitivity with the larger circular objects that varied in thickness (physical contrast) and visibility of detail and calcifications with the "star shaped" clusters of simulated calcifications that are marked. Each cluster contains calcifications of specific sizes as shown. Image quality is evaluated by determining the highest-numbered cluster in which the calcifications can be seen. This gives a measure of the smallest calcifications that can be seen.

Blurring and Visibility of Detail and Calcifications

As with all imaging methods, it is the blurring within the imaging process that reduces and limits the visibility of small objects and detail. Effective mammography requires the ability to see the physical details, such as size and shape, of these micro calcifications. Therefore, mammography systems must be designed and operated to produce the least amount of blurring of any medical imaging process.

A general assumption or "rule of thumb" suggested by the author is that for an anatomical object to be visible in an image the dimension of the blur should not exceed the dimensions of the object. This is generally demonstrated in mammography. The effective blur values of typical mammography systems are in the range of 0.15 mm to 0.2 mm which is the approximate size of the smallest micro calcifications that can be visualized. Among all of the medical imaging methods, mammography is the one that requires the least blurring of all.

It is this requirement for very low blurring that has been one of the challenges and major objectives in the development, design, and operation of mammography systems over the course of its history.

Mammography System Composite Blur

The blur in a mammogram is the composite blur from the three major sources: receptor, focal spot, and motion. The source that produces the largest blur is generally the one that limits visibility and image quality. Because there are other factors associated with each source of blur, including focal spot heat capacity and the x-ray attenuation by receptors, there are limits to reducing these blur sources to very small values. In general, an optimized mammography procedure, with respect to blurring, is when the blur from the individual sources are about equal, unless one can be reduced more without compromises. Each of these has been addressed in the ongoing development of mammography.

The contribution of blur from each of the sources depends on the geometry or spatial relationships of components of the imaging system as illustrated in Figure 25.

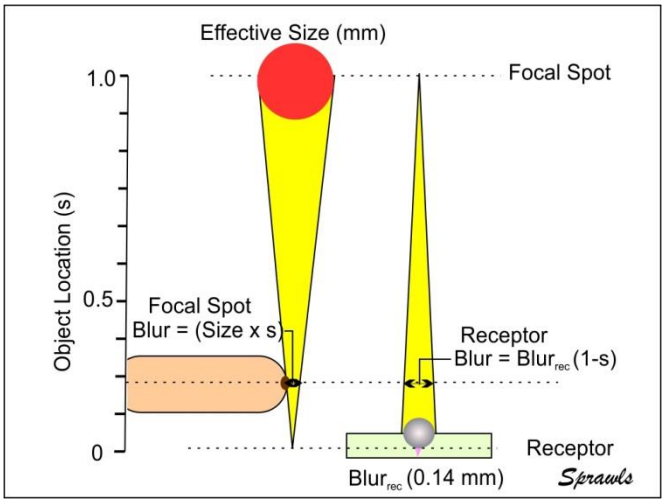

Figure 25. The effect of breast location ("s" scale) between the receptor and focal spot on the blur from those two sources.

The effect of blur on image quality and visibility of detail depends on the dimension of the blur in relationship to the dimension of an object. The geometric magnification within the imaging process is a factor in this relationship. Blur from the different sources is either magnified or minimized by the geometry as they relate to the location of the breast and objects to be imaged. Therefore, it is most appropriate to consider the dimensions of the blur at the location of the object. This relationship has been a major factor in the development of mammography over the years.

Effect of Breast and Object Location on Blurring and Visibility of Calcifications

The geometric configuration or spatial relationship of the focal spot, receptor, and breast for a mammographic procedure has been a major factor in image quality and has evolved along with other developments. The effect of breast location on image quality is best quantified using the "s" scale, rather than magnification factor as illustrated in Figure 25. This scale developed and published by the author (Sprawls) shows the location of the object being imaged, the breast, as a proportional distance between the receptor and the focal spot. The scale ranges from a value of "0" at the receptor to a value of "1.0" at the focal spot. Using this scale the value of the blur at the location of the object, where it directly relates to the size of the object, (calcifications, etc.) is a linear function of object location as shown in Figure 25. This applies to both focal spot and receptor blurring.

Receptor Blur

The necessity for reduced blurring was the major factor for selecting directly x-ray exposed film rather than intensifying screens in the early development of mammography. Intensifying screens were used in general radiography at that time but their inherent blur, and when used with double-emulsion film and some light crossover, were not adequate for mammography.

The development of intensifying screens specific for mammography in the 1970s was a major evolution because it provided for a significant reduction in radiation dose to the patient. The features of intensifying screens for mammography is compared to general radiography were compared in Figure 21.

XII. X-RAY TUBE FOCAL SPOTS FOR MAMMOGRAPHY

The x-ray tube focal spot has been a continuing challenge in mammography and has evolved with advances in technology in the quest for increased visibility, especially micro calcifications and anatomical detail. As we have just observed, the value and effect of focal spot blurring on visibility is determined by the combination of two factors, the effective size of the focal spot and the specific location of the breast between the receptor and the focal spot, along the "s" scale. Both of these have evolved over the years. This has included the development of tubes specific for mammography and dedicated equipment with generally fixed geometry.

Effective Focal Spot Size

The common practice in x-ray tube technology is to use two different quantities to express the size of focal spots. One is the *actual physical* or so called *"nominal" size* that can be measured by making images with a pin-hole camera or similar device. This is the size generally provided by the manufacturer within some relatively large tolerances. The *effective* (blur) size is what determines image quality. This is measured with star or line-pair resolution test patterns as often done by

physicists in quality assurance procedures. For a specific focal spot the effective value is always larger than the nominal because of several factors. The radiation distribution within the focal-spot area is not uniform--often two peaks because of the focusing characteristics of typical x-ray tube cathodes. This produces blurring as if it was a larger focal spot with either a uniform or Gaussian distribution of the radiation. A second factor is that the "nominal" size indicated on the label makes use of a tolerance factor so that it is actually smaller than the real physical size.

It is the effective size, as measured with test patterns that can be directly compared to the effective blur values of receptors to determine overall composite blur of an imaging system as it affects image quality. For each focal spot and receptor combination there is a breast location where the combined or composite blur has its minimum value. That is a significant factor in the design of mammography systems and has evolved over the years. With respect to focal spot size and system geometry there have been three major phases in the development of mammography as illustrated in Figure 26.

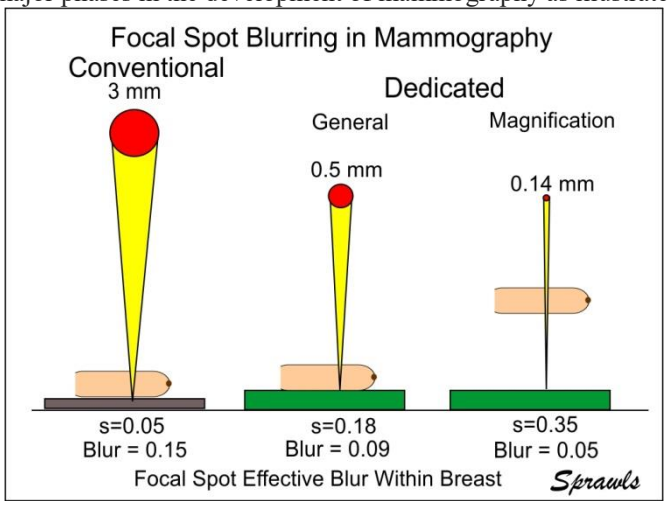

Figure 26. Three focal spot sizes that have been used in mammography.

Conventional X-Ray Tubes

In the early stages of mammography development conventional tubes with relatively large focal spots were used. They were available and the heat capacity of the larger focal spots was needed to produce high exposures in the shortest time possible with the directly exposed film. However, the geometry compensated for the large spots to minimize blurring. The focal spot-to-receptor distance was relatively long and the breast was very close to the film receptor.(s= 0.05). This was the combination that provided good visualization of calcifications and helped established mammography as a major method for detecting and managing breast cancer.

X-Ray Tubes for Mammography

With the clinical value of mammography having been demonstrated by Egan and others using conventional x-ray systems, often with some modifications, the motivation to develop x-ray tubes designed specifically for mammography was established. The various features of these tubes included special anode materials as described earlier. Also most systems placed the tube cathode towards the chest using the Heel effect to reduce intensity at the thinner side of the breast.

Here the attention is on x-ray tube focal spots. The tubes developed and used in more recent dedicated systems typically had dual focal spots with nominal sizes of 0.3 mm and 0.1 mm. The corresponding effective sizes (relating to blurring) are approximately 0.5 mm and 0.14 mm illustrated in Figure 26. Some designs, especially for the smaller focal spots, used a method that focused the electron beam on the anode in a more Gaussian pattern that contributed to smaller effective (blurring) sizes in relationship to physical (heat capacity) size. The smaller focal spots for mammography, compared to conventional radiography tubes, were possible because of a combination of factors. With the use of intensifying screens the exposure (anode heating) was reduced and with a smaller field of view a more favorable anode angle could be used.

Magnification Mammography

The ability to use geometric magnification to improve image quality and the visualizations of micro calcifications was a significant development in mammography. With the availability of small focal spots geometric magnification can be used to reduce the effective receptor blurring as illustrated in Figure 27.

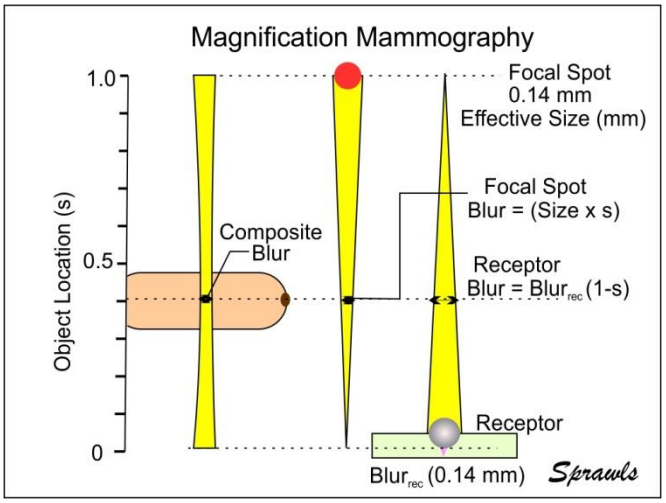

Figure 27. The use of geometric magnification to reduce the effective receptor blurring and increase visibility of small calcifications.

A major factor contributing to the value of this procedure is that the value of the composite blur from the two sources is less than the sum of the two values. It is a convolution or "overlap" of the two blurs. This advantage and improved visibility is achieved when focal spots with sizes smaller or close to the blur values of the receptors are available.

In 1977 Radiological Sciences, Inc. developed an x-ray tube with a very small focal spot size. One of the first units was installed in our laboratory at Emory combined with breast supports for performing magnification. A combination of physics and clinical investigations demonstrated the value of magnification to enhance visibility of detail and calcifications. Other researchers demonstrated the value of the magnification technique in extensive clinical studies. Dual focal spot tubes with a smaller spot for magnification as described previously became the standard for dedicated mammography systems.

XIII. RADIATION EXPOSURE AND DOSE IN MAMMOGRAPHY

The major goal in the continuing development and innovations in mammography was image quality and visibility within the breast. Its clinical value depended on that. A prevailing challenge was controlling the radiation dose to the breast. This was especially significant because of two factors: one is biological and one is physics. The biological is the relatively high sensitivity of breast tissue to undesirable biological effects from x-radiation compared to other anatomical regions. The physics issue is the dependence of several image quality characteristics on the quantity of radiation used to produce an image. With mammography requiring higher image quality than other radiographic methods it is inherently a high exposure procedure.

Breast Entrance Skin Exposure (ESE)

One of the activities often performed by physicists was determining the radiation exposure or dose to a patient. In the early period of mammography this was generally limited to determining the exposure delivered to the surface of the breast. This was done by calibrating the exposure output of the machine and then calculating from the technique factors (KV and MAS) actually used in a procedure. An alternative was placing TLDs on the breast.

The surface exposure was used to compare different methods and procedures but did not provide a dose value that was appropriate for evaluating biological risk. Some approximate surface exposure values for the different phases of receptor development are:

- Direct exposed industrial type film – 6,000 mR.
- Xeroxmmmography – 3,000 mR.
- Film with intensifying screens – 1,000 mR

These values illustrate two significant factors that mammography is a relatively high-exposure procedure and the required exposure was reduced with developments in receptor technology.

Mean Glandular Dose (MGD)

The concept of mean glandular dose (MGD) was developed as a quantity that would be more related to the biological effect of the radiation. It is defined as the average radiation absorbed dose to the breast glandular tissue and became the standard for monitoring dose in clinical procedures, evaluating equipment performance in quality control activities, and for some regulatory limits.

It is determined by multiplying the surface exposure value by a conversion factor that has been developed by physicists for a range of breast sizes and x-ray spectra characteristics generally specified with HVL values. For an average breast and typical imaging procedure a 1R SES will result in a MGD of 108 mR.

Two of the major factors that determine exposure and dose to a breast are the penetration characteristics of the radiation through the breast and the sensitivity, or required exposure, to the receptor. Both of these have evolved in the development of mammography.

Receptor Sensitivity and Required Exposure

Significant reduction in exposure and dose resulted in the transition of directly x-ray exposed film to the use of intensifying screens. Receptors for mammography continue to require a relatively high exposure to control quantum noise because of the very low blurring characteristic.

X-ray Penetration through the Breast

The effect of the x-ray spectrum on the opposing requirements for high contrast sensitivity (in soft tissue) and reducing radiation dose has been a major factor in the continuing developments in mammography. The goal is to adjust for an *optimized* spectrum for each breast size and density. A major contribution was the introduction of molybdenum and rhodium as anode and anode and filter materials. Compression and measurement of the thickness of the breast contributes to this effort. The training and experience of the mammographer / technologist is a critical factor in conducting an optimized procedure with respect to image quality and dose.

In addition to these two major factors that have evolved over time the introduction of grids and the magnification technique resulted in some increase in exposure and dose but are considered to be appropriate because of the increased image quality.

XIV. CHRONOLOGY OF DEVELOPMENTS IN MAMMOGRAPHY

The physics and technological developments to increase the clinical effectiveness, manage risks, and improve the overall efficiency of mammography have continued for well over a half century, and with more to come. It is appropriate to summarize by relating some of the major developments to the times when they occurred. This gives a valuable perspective to the scope of physics contributions to this medical specialty and the preservation of life and health for society around the world in specific decades.

The 1960s…The foundation

This was the period in which mammography began to be developed as a major medical procedure especially with the pioneering work and contributions of Drs. Robert Egan in the USA and Charles Marie Gros in France. Both were physicians but were major contributors to the application of physics and development of the technology for imaging the breast. By using the technology and methods developed under their leadership and in their collaborations with physicists and engineers they demonstrated, promoted, and expanded the clinical application through extensive educational and organizational activities. The technology at that time consisted of conventional x-ray equipment, tubes with tungsten anodes, and receptors consisting of industrial type film exposed directly by the x-radiation. The imaging procedure did not generally include compression and stabilization of the breast. In 1969 this decade was concluded with a major breakthrough, the development of the first dedicated mammography equipment that included a molybdenum anode and filter, the CGR Senographe.

The 1970s…Development of Modern Mammography Technology and Methods

The major physics and technology developments establishing mammography as a valuable and practical method for diagnosing and managing breast cancer occurred during the 1970s.

The first dedicated equipment, the Senograph, introduced in 1969, spread around the world along with dedicated systems developed by other manufacturers.

In 1973 the Siemens Mammomat and the Philips MammoDiagnost, Toshiba and Picker Mammorex were introduced. In 1974 General Electric introduced the dedicated MMX system.

In 1977 Radiologic Sciences Inc. provided a tube with a very small focal spot that stimulated the development of the magnification technique. This technology was acquired by Pfizer in 1979 and then by Elscint in 1981.

In 1978 Philips added an anti-scatter grid that was developed for mammography.

It was the decade for the development of image receptors for mammography to replace the industrial type film that required relatively high radiation exposures.

In 1971 Xeroradiography was introduced and was used for several years, generally the interval between directly exposed film and the development of intensifying screens specific for mammography.

In 1972 DuPont developed the Lo-dose calcium tungstate screen-film system contained in an evacuated bag to provide good film-screen contact during exposure.

In 1976 DuPont introduced the Lo-dose/2 screen-film system and Kodak the Min-R system using a rare earth screen. These were in rigid cassettes, much easier to use than the vacuum bags. Also, Agfa Gavert entered the market with a film screen cassette for mammography.

The 1980s…Refinements to Technology and Attention to the Total Mammography Operation

This decade began with mammography being performed with dedicated equipment and state of the art film-screen receptors. It was not to be a time for major innovations. Equipment features including automatic exposure control (AEC) were being refined. There were some advances in general radiography film design, the introduction of tabular "T" grain that was also used in mammography.

In 1987 the American College of Radiology (ACR) began its Mammography Accreditation Program, the ACR MAP. This was for Facilities that performed mammography. It was not a government legal requirement but some medical insurance providers would only pay for services in an accredited facility. There were a number of conditions required for accreditation including use of approved equipment and education of staff. A significant requirement was periodic quality control evaluations performed by qualified medical physicists.

This was the beginning of quality control procedures with specified image quality requirements, testing methods, and reporting that were to become a major role for medical physicists in mammography.

The 1990s…Image Quality Control and Personnel Qualifications

This was the decade in which emphasis transitioned from developments in new technology to the factors associated with the total mammography process including human performance. A major objective was to ensure that the high image quality available with the equipment and imaging procedures of that time was being achieved and contributing to accurate diagnosis and management of breast cancer. Medical physicists were to be a highly significant part of this development

In 1992 the American College of Radiology (ACR) published the *Mammography Quality Control Manual for Radiologists, Radiologic Technologists, and Medical Physicists.*
This provided detailed instructions and procedures for all …

In 1994 the USA Food and Drug Administration (FDA) implemented the Mammography Quality Standards Act (MQSA). This was a major action in which virtually all aspects of quality in mammography became regulated by federal legislation and law.

XV. AND THEN THERE WAS DIGITAL

The decades of the 2000s were to be the era of a major transition in mammography, from *film* to *digital* receptor, viewing, and image archiving technology and methods.

In 2000 the USA FDA approved the first digital system. The GE Senographe 2000D, for clinical use. Others were to follow.

The history of digital mammography is "another story for another day" and is not included here. The interests here are some of the factors associated with digital that brought to an end the use of film as the receptor element for mammography.

Photographic type film, a radiation sensitive emulsion coated on a transparent base, was, along with fluorescent intensifying screens, the foundation of radiography for over a century because of its many valuable characteristics. These included converting invisible radiation into visible images, an easy to view display, which could be stored and archived. However, along with these many values there were challenges and disadvantages that contributed to its replacement with digital technology. These included:

- An expensive silver based commodity that could be used only one time
- Required precise and accurate exposure to capture contrast from the breast.
- Required expensive, time and labor consuming, and somewhat unstable chemical processing.
- After being exposed and chemically processed images cannot be changed or adjusted, often requiring repeated exposures to correct for technique factor errors.
- Transporting and managing mammograms within a facility requires considerable time and effort.
- For an image on film viewing factors including brightness, contrast, and magnification cannot be adjusted.
- Archiving and retrieving images on film requires time and labor in addition to space with controlled environmental conditions.

Digital imaging technology provided solutions for all of these limitations, including:

- The wide exposure dynamic range of digital receptors that overcomes the prevailing latitude limits of film and related variations in breast size and composition.

- Images quickly transferred electronically from receptor to viewing display…without manual labor and chemical processing.
- Ability to control image viewing conditions to enhance visibility over a range of breast sizes and compositions.
- Electronic management, archiving, retrieval, and distribution of mammograms, almost "at the speed of light".

In addition to replacing and bringing to an end the use of film as a receptor digital technology made possible the development of the next major innovation in mammography, *tomosynthesis*.

And with that we conclude this history of the major phase in the development and evolution of mammography in which film served many valuable functions, from receptor element to display for viewing and archiving.

XVI. BIBLOGRAPHY

The historical evolution of the physics and technological developments in mammography has been researched and published by many who were often themselves active contributors to the ongoing activity. Their publications often contain details of specific developments beyond what is described in this article. They also provide extensive literature references to the science and clinical research contributing to the development of mammography.

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- Vyborny, CJ, Schmidt, RA, Mammography as a radiographic examination: An overview Radiographics. Volume 9, Number 4 July, 1989 https://doi.org/10.1148/radiographics.9.4.2667052
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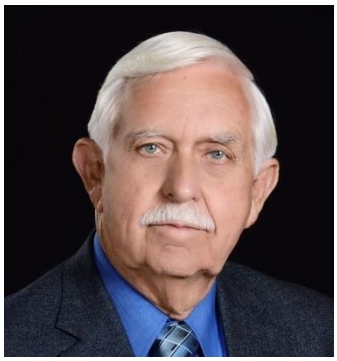
- Joe, BN, Sickles, EA. The Evolution of Breast Imaging: Past to Present Radiology Vol. 273, No. 2S. 2014 https://pubs.rsna.org/doi/full/10.1148/radiol.14141233

XVII. ABOUT THE AUTHOR

Perry Sprawls. PhD, is a medical physicist and engineer specializing in diagnostic medical imaging. Mammography has been a major focus of his efforts including research and development, clinical support and procedure optimization, quality control and assurance, and extensive educational activities.



He joined the Emory University faculty in the 1960s and there was a collaborator with Robert Egan, MD, the "father of mammography" for many years in the continuing development of mammography technology, methods and applications. He gave special emphasis to the value of medical physicists working directly in clinical mammography facilities and in collaboration with radiologists and technologists to enhance image quality and related functions. In addition to his University and clinical activities he was a consultant and collaborator with several of the major developers and manufacturers of mammography image receptors. His mammography physics educational materials are available for all to use at: www.sprawls.org .

The collaborators who have been major contributors to his career in mammography are: Debra Monticciolo, MD, formerly at Emory, now at Texas A&M University Health Sciences; Earle Lee Kitts Jr., PhD, DuPont scientist; and Arthur G. Haus, FAAPM, Kodak scientist and medical imaging historian.

XVIII. ADDEDNIUM

Review of the Physics of Mammography

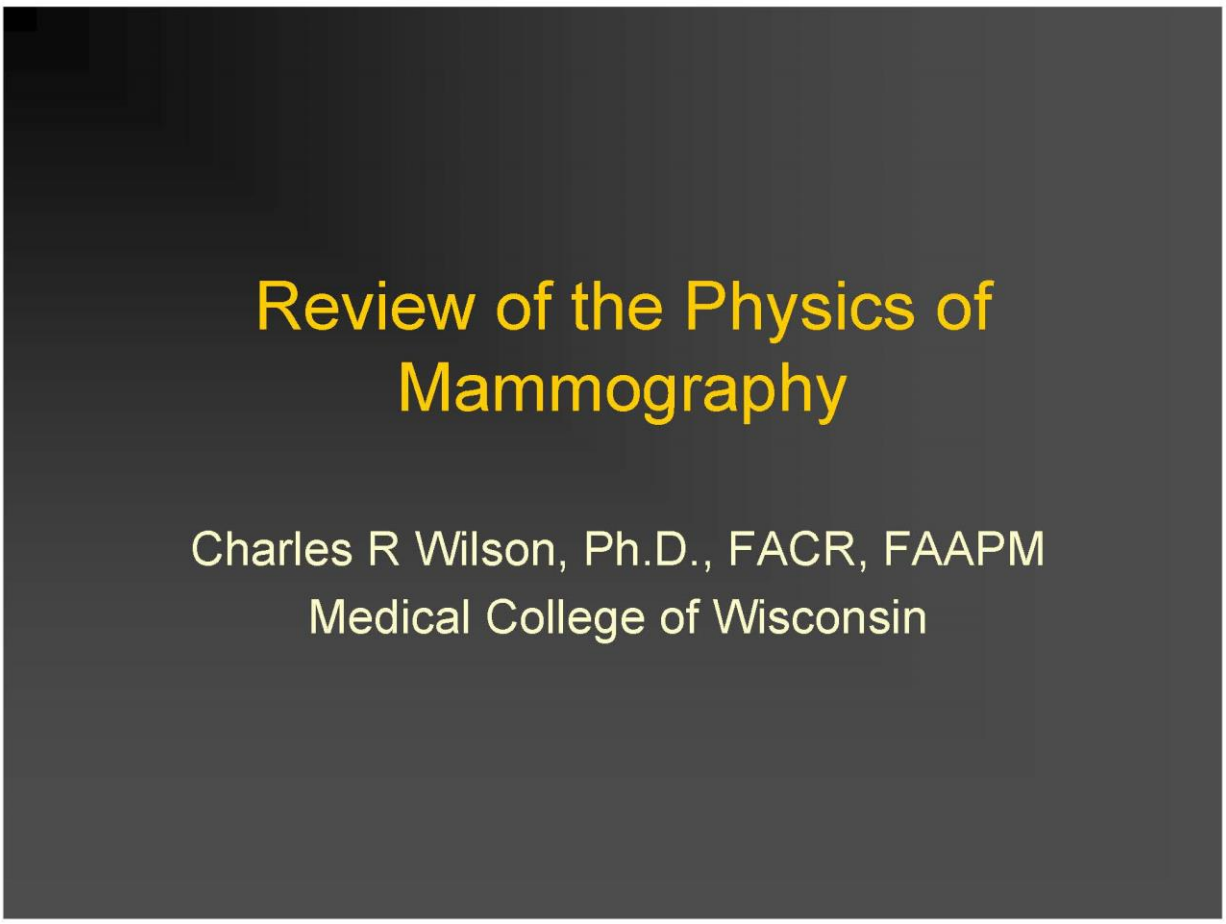
This course was presented at an American Association of Medical Physicists Annual Meeting. It provides an overview and extensive details covering the continuing developments of the technology and methods that document much of the history of mammography.

Charles R. Wilson, PhD, FAAPM, FACR
Medical physicist specializing in x-ray imaging
and related activities.

The contribution of Dr Charles R Wilson to this chapter of the Medical Physics History project is gratefully acknowledged.

Further down in the text follows the presentation of Dr Wilson as PDF in standard resolution.

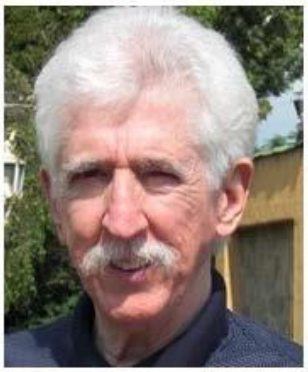
The High resolution PDF of this presentation can be downloaded here.

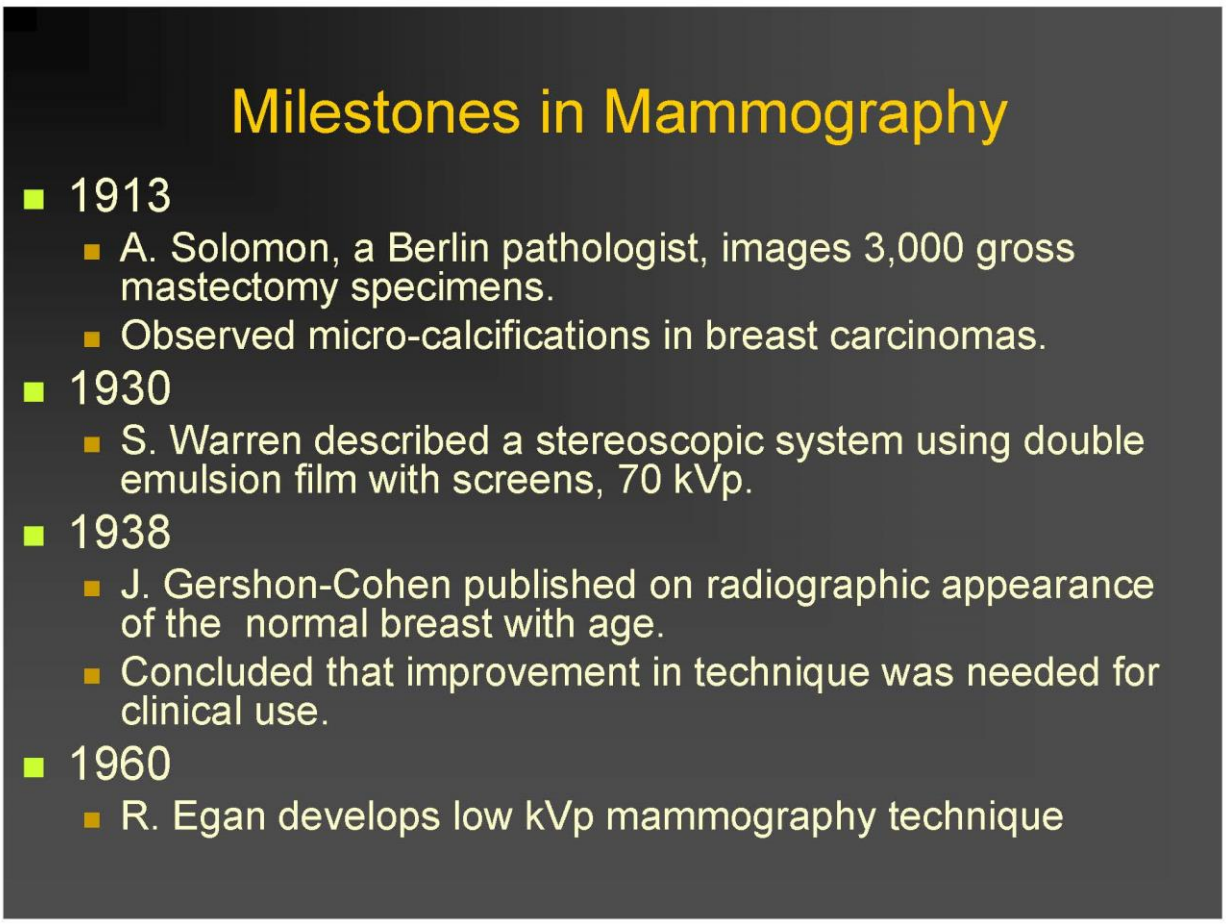

Review of the Physics of Mammography
Charles R Wilson, Ph.D., FACR, FAAPM
Medical College of Wisconsin

This course was presented at an American Association of Medical Physicists Annual Meeting

It provides an overview and extensive details covering the continuing developments of the technology and methods that document much of the history of mammography.

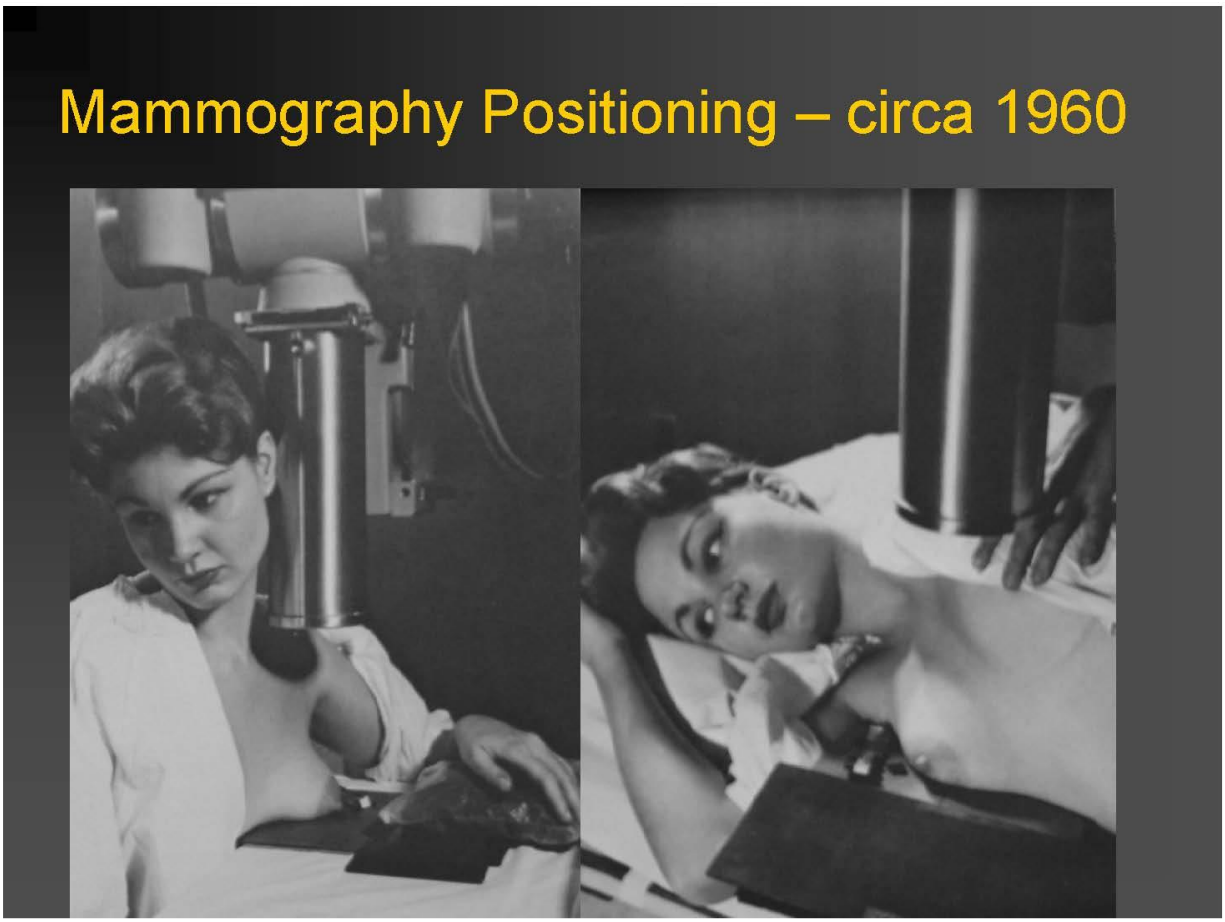
Charles R. Wilson, PhD, FAAPM, FACR
Medical physicist specializing in x-ray imaging and related activities at the
MEDICAL COLLEGE OF WISCONSIN

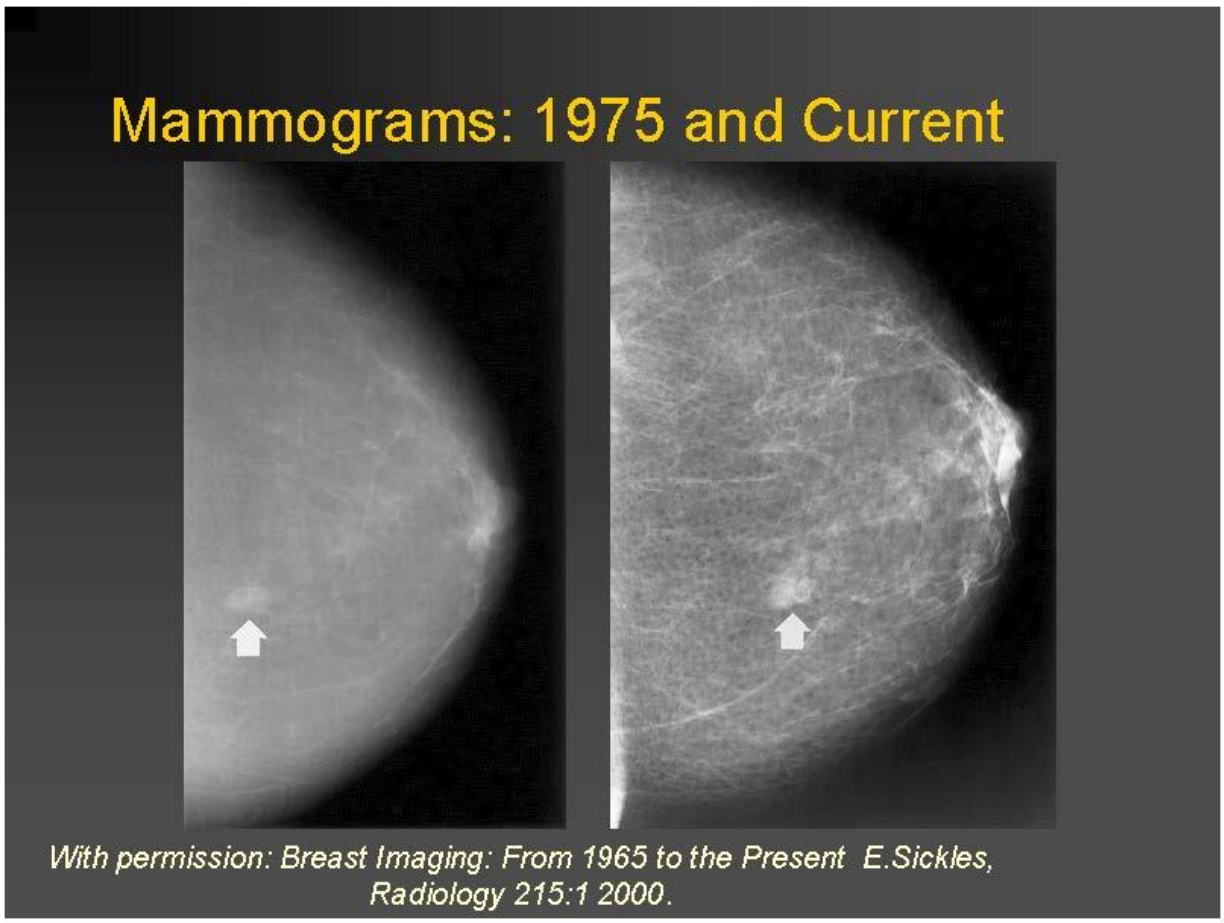


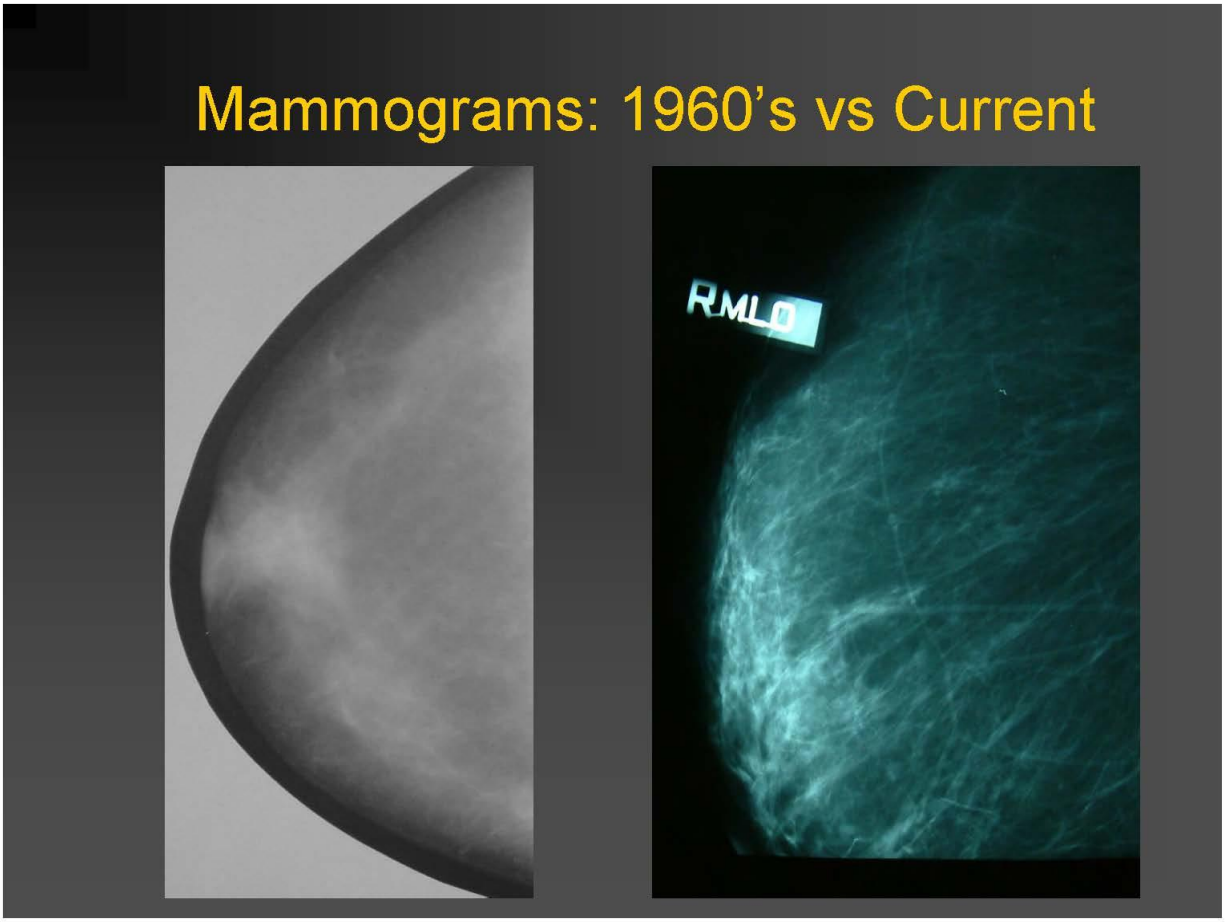

Milestones in Mammography
1913
A. Solomon, a Berlin pathologist, images 3,000 gross mastectomy specimens.
Observed micro-calcifications in breast carcinomas.
1930
S. Warren described a stereoscopic system using double emulsion film with screens, 70 kVp.
1938
J. Gershon-Cohen published on radiographic appearance of the normal breast with age.
Concluded that improvement in technique was needed for clinical use.
1960
R. Egan develops low kVp mammography technique

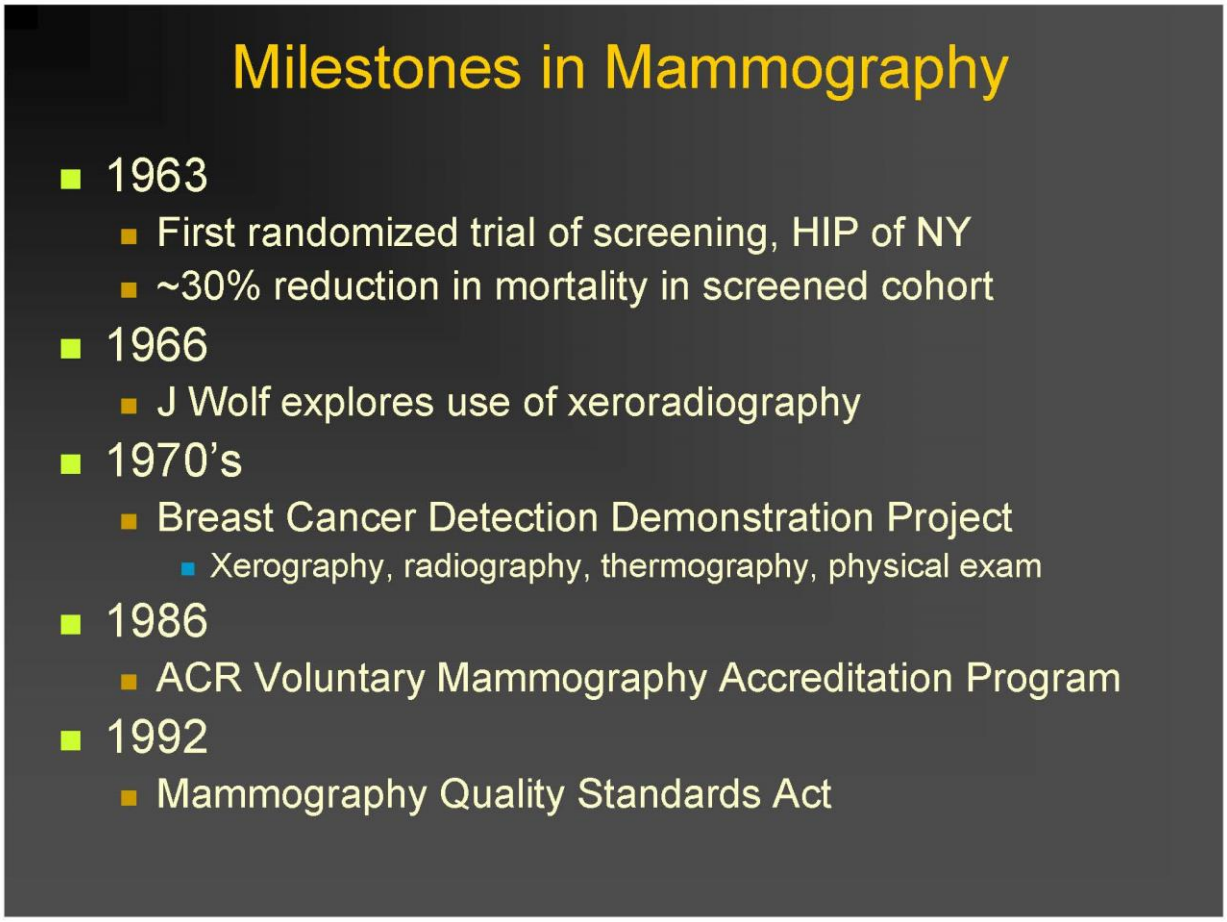
Robert Egan's Technique – 1960's

- Low kVp technique
  - verified kVp using a 15 mm Al wedge
- Beryllium window x-ray tube with minimum filtration
- Space charge limitations resulted in long exposure times, ~6 seconds
- Long SID: reduce focal spot blurring and provide adequate field coverage
- Metal extension cones: no field light
- Fine-grain industrial film
- No grid


Mammography Positioning – circa 1960

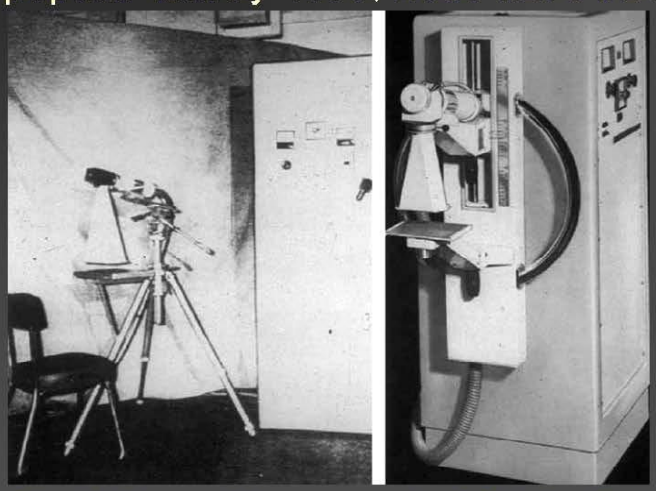

Mammograms: 1975 and Current
With permission: Breast Imaging: From 1965 to the Present E.Sickles,
Radiology 215:1 2000.


Mammograms: 1960's vs Current
RMLO


Milestones in Mammography
1963
First randomized trial of screening, HIP of NY
~30% reduction in mortality in screened cohort
1966
J Wolf explores use of xeroradiography
1970's
Breast Cancer Detection Demonstration Project
Xerography, radiography, thermography, physical exam
1986
ACR Voluntary Mammography Accreditation Program
1992
Mammography Quality Standards Act

First Dedicated Mammography Unit

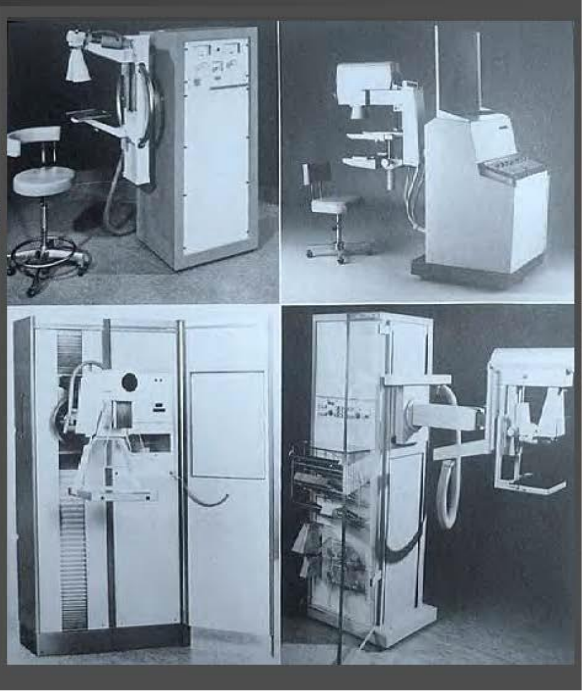
- 1965
  - Charles Gros, MD, Strasbourg, FR
  - CGR Senographe (Breast in French is Sein)
  - Very popular unit by 1970, 2000 were installed world-wide



With permission: Short History of Mammography: A Belgian Perspective, A. Van Steen, R. Van Triggelen, JBR-BTR, 2007.

Dedicated Mammography Units

- 1973
  - Picker (Mammorex),
  - Siemens (Mammomat)
  - Philips (Diagnost)
- 1974
  - GE (MMX)



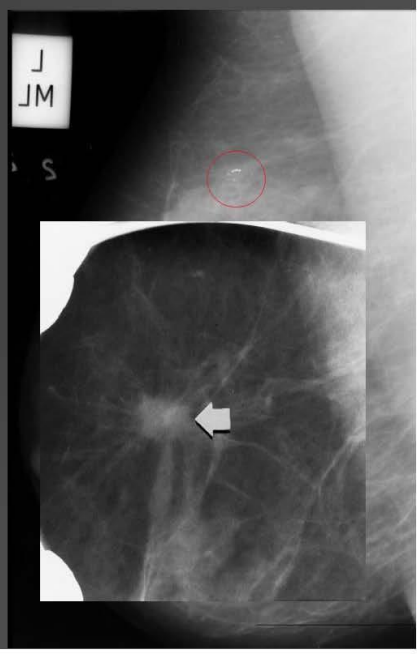
Current Dedicated Mammography Unit

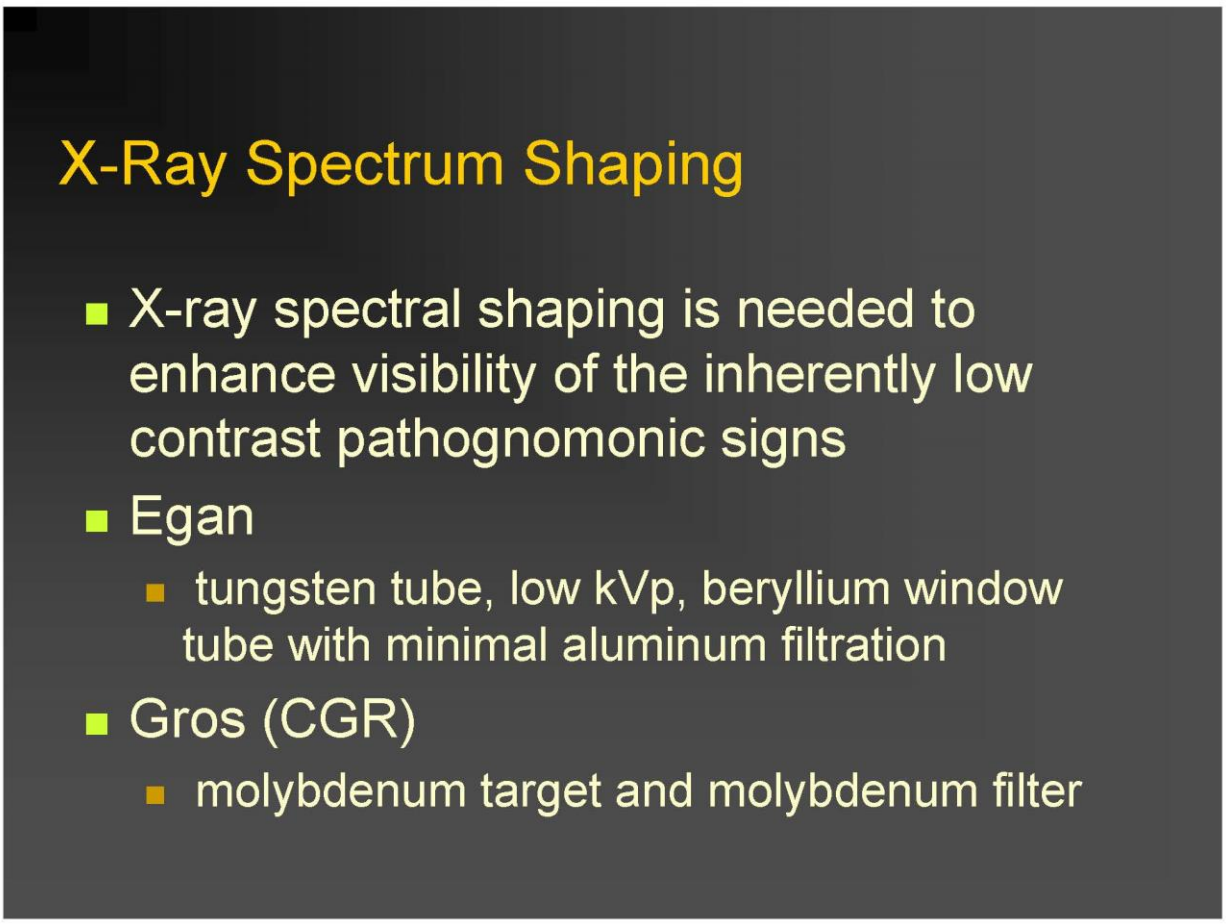
- Gantry mounted x-ray and detector assemblies
- X-ray tube target/filtration and focal spot appropriate for mammography
- Compression device
- AEC
- Film/screen and grid designed for mammography
- Dedicated film processor

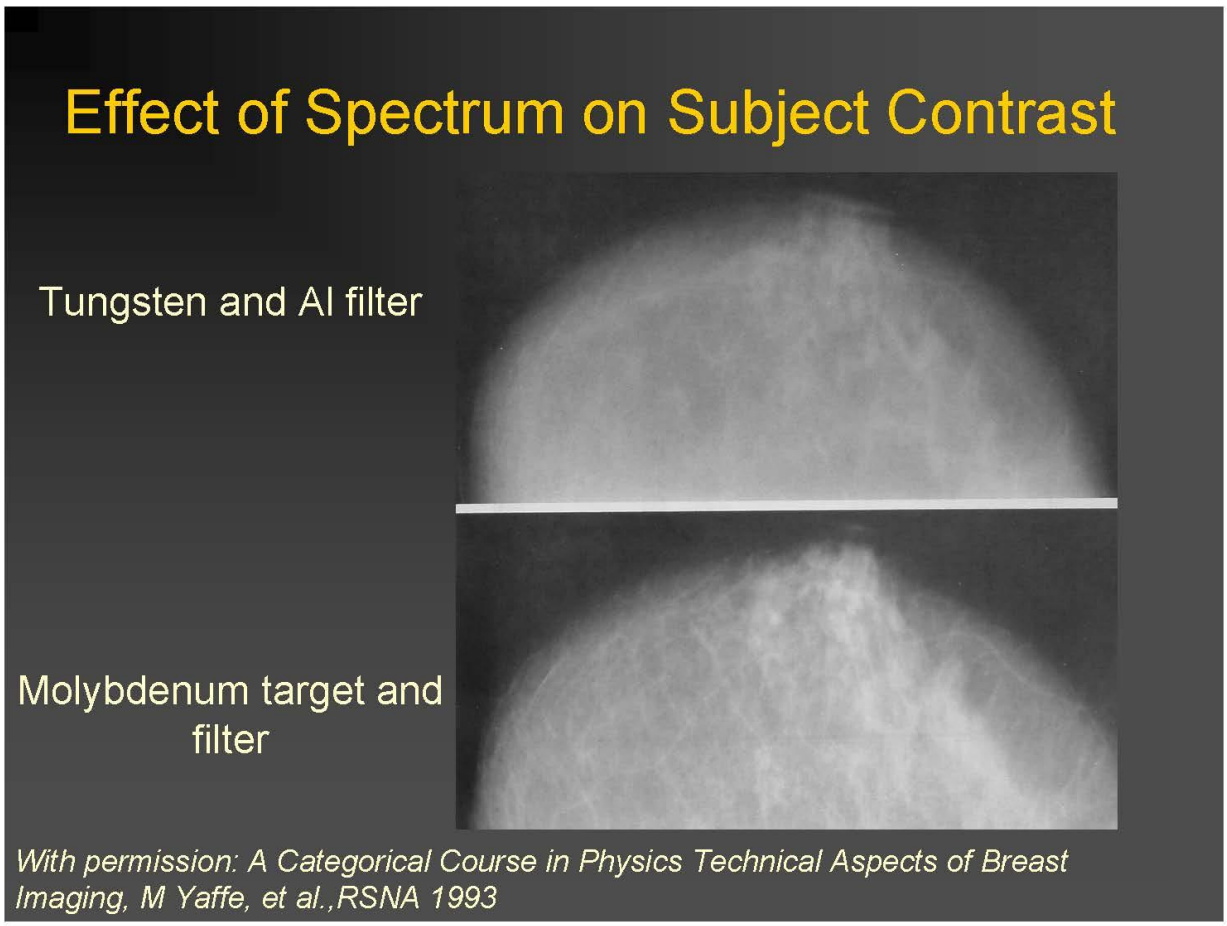
Pathognomonic Signs of Breast Cancer

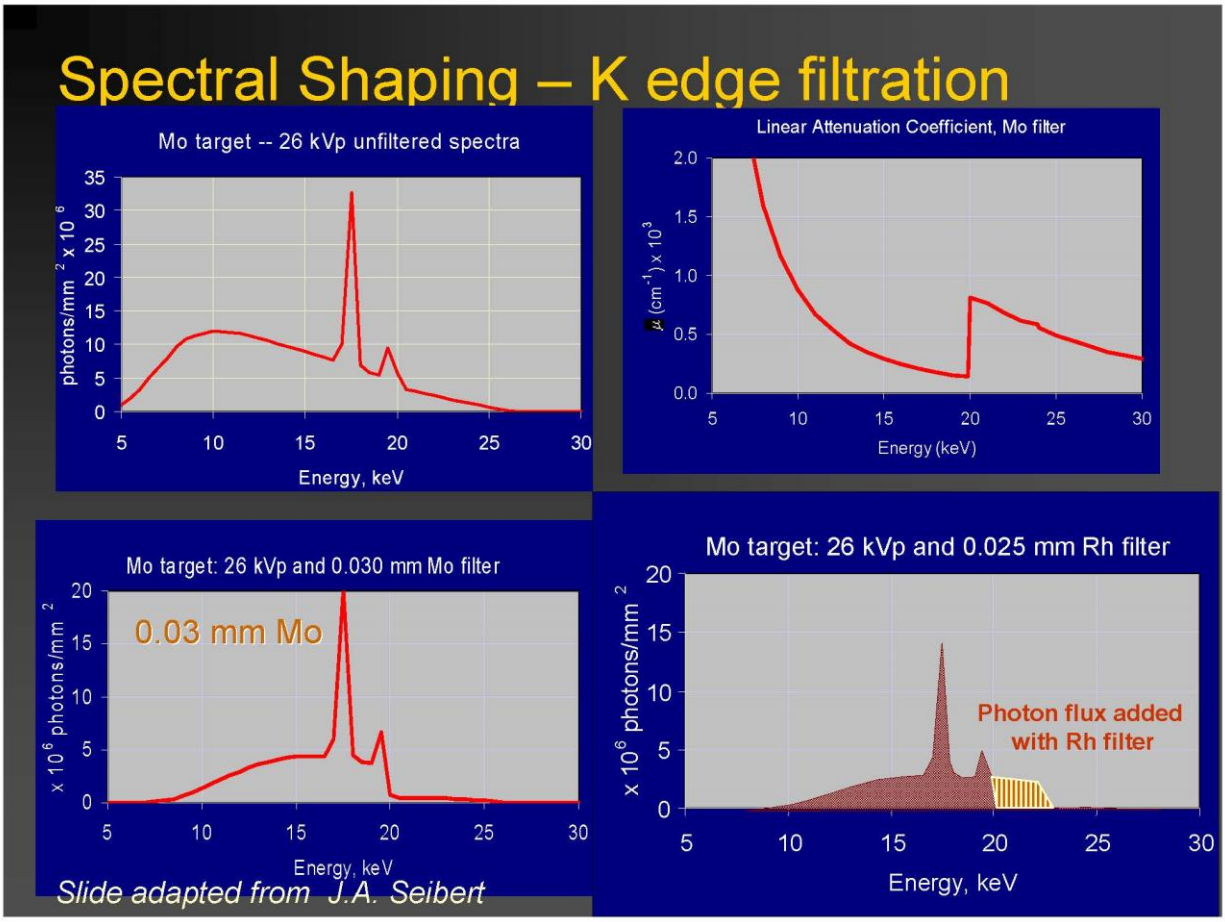
Small Details With Inherent Low Subject Contrast

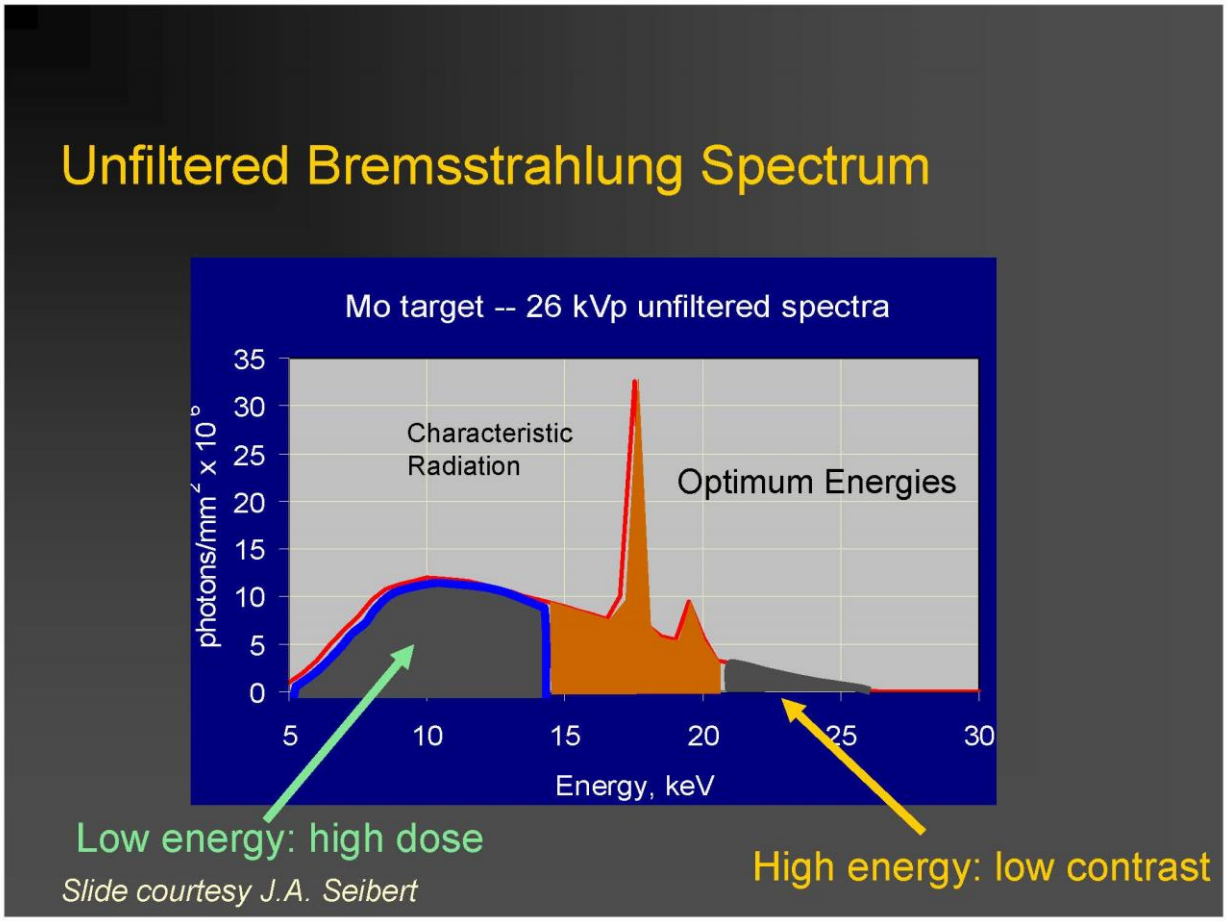
- Masses
  - spiculated
  - shape and margins are important
- Micro-calcifications
  - 100 to 300 microns
  - shape and distribution important
- Others
  - Asymmetric densities
  - Architectural distortions

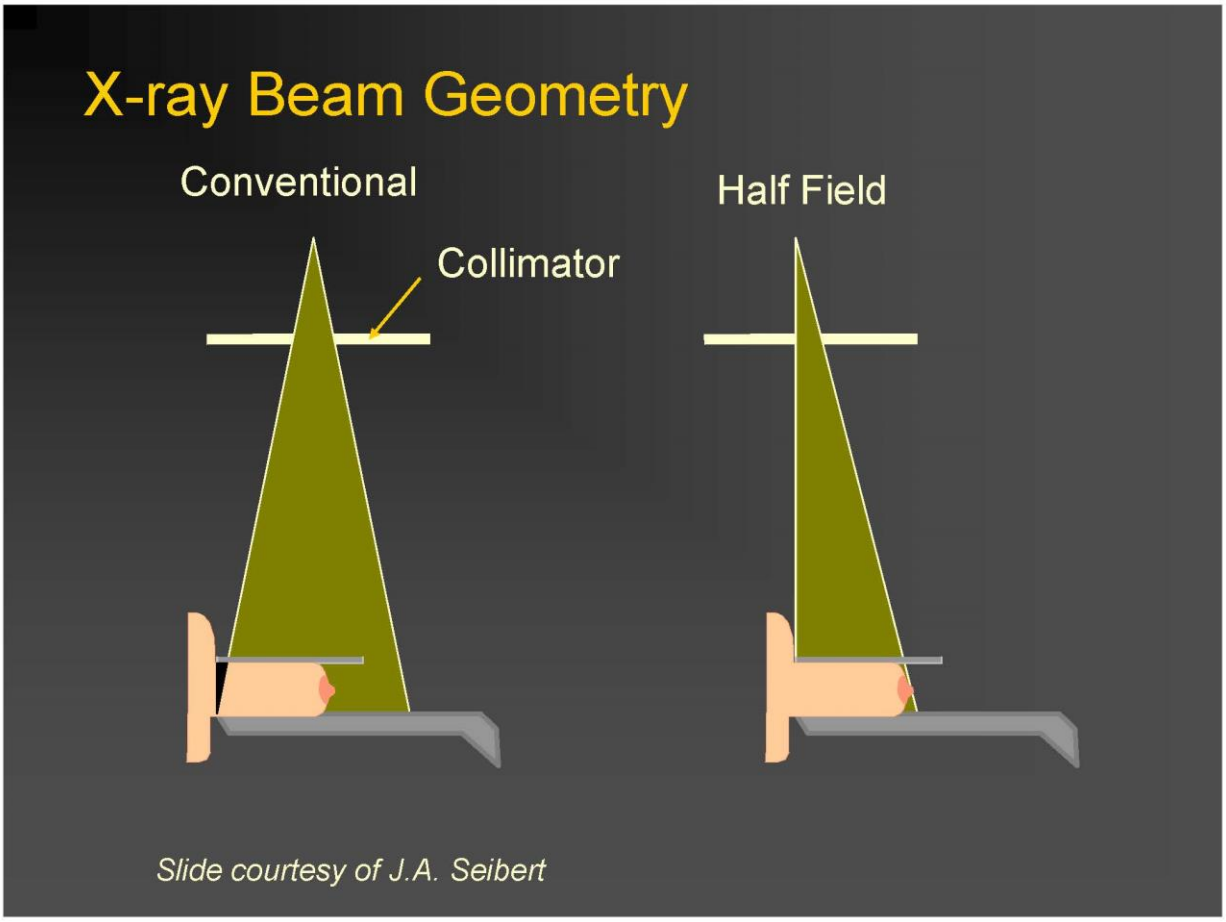


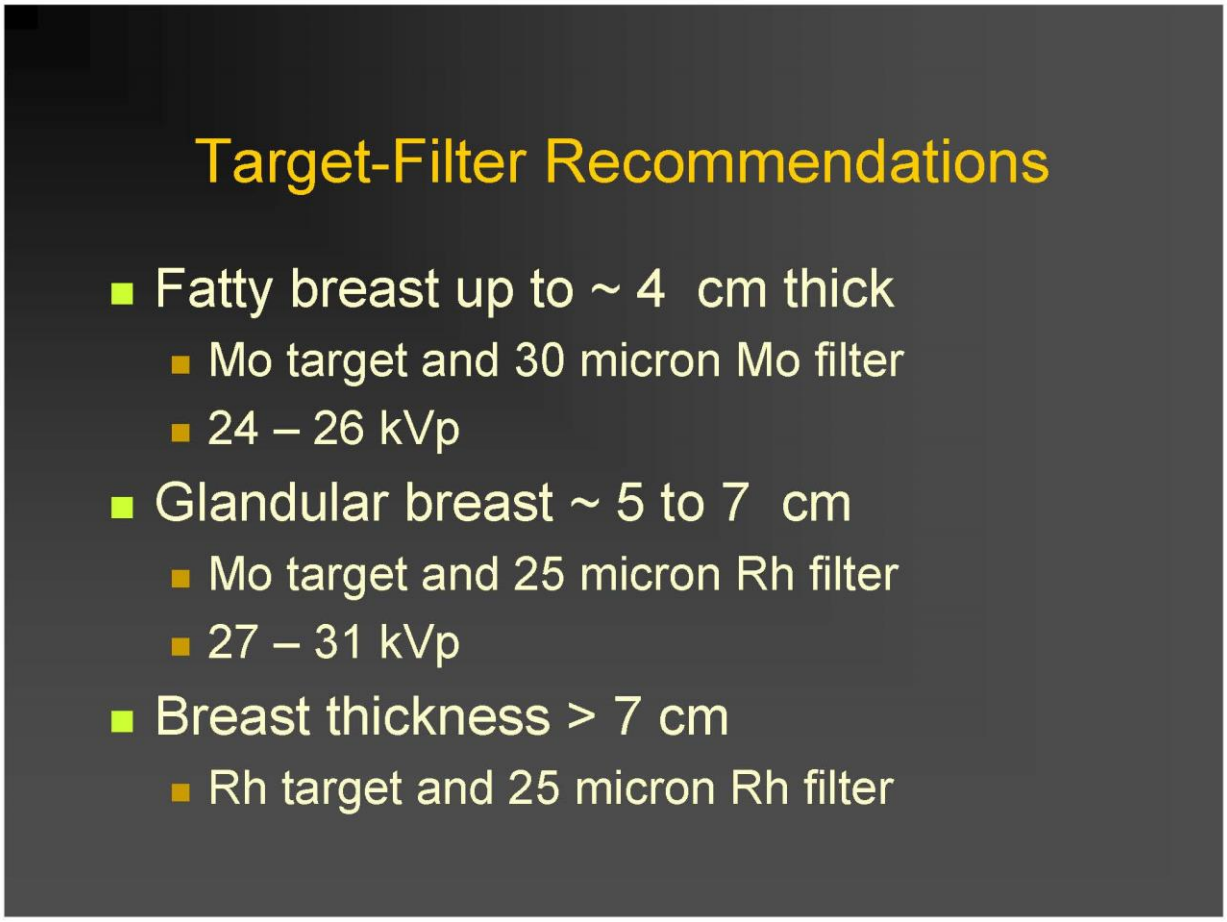

X-Ray Spectrum Shaping
X-ray spectral shaping is needed to enhance visibility of the inherently low contrast pathognomonic signs
Egan
tungsten tube, low kVp, beryllium window tube with minimal aluminum filtration
Gros (CGR)
molybdenum target and molybdenum filter

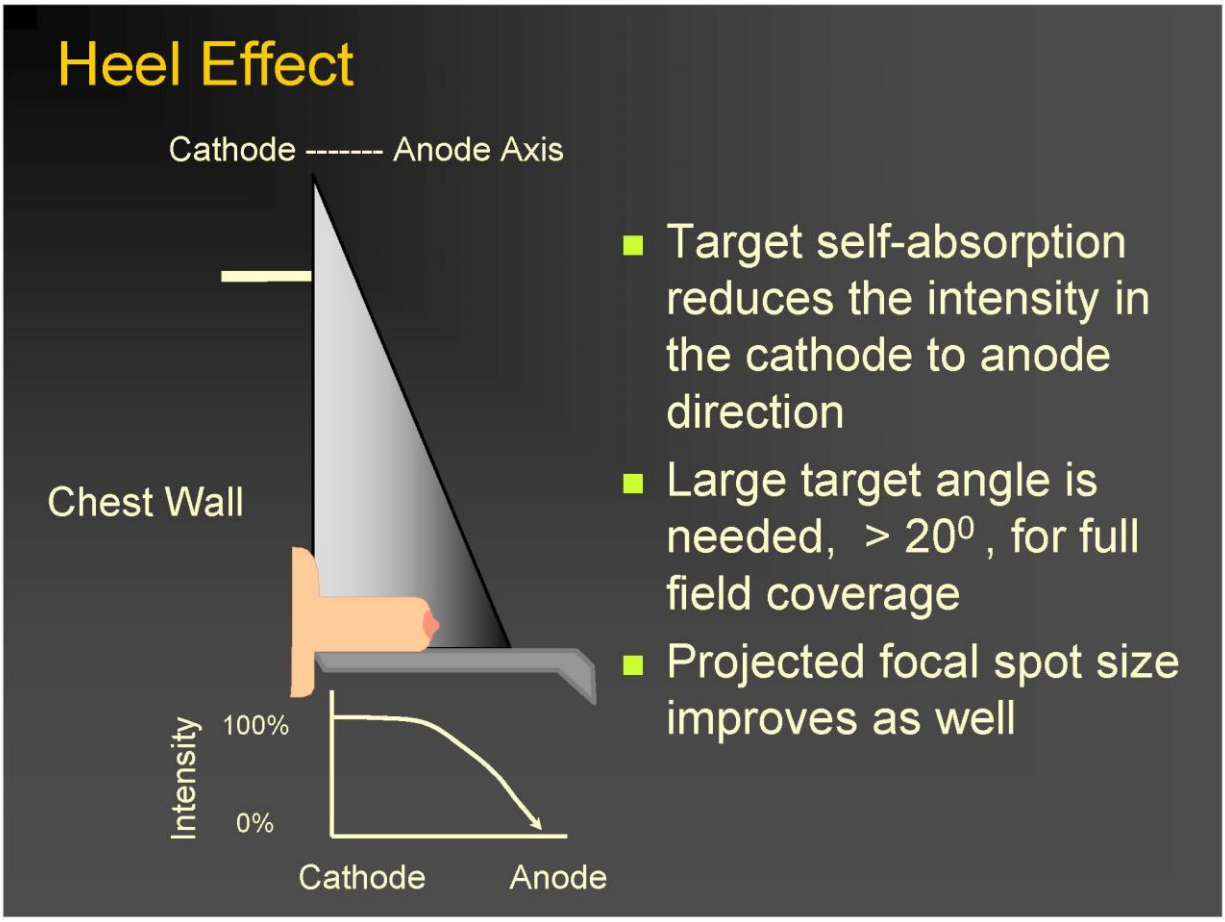

Effect of Spectrum on Subject Contrast
Tungsten and Al filter
Molybdenum target and filter
With permission: A Categorical Course in Physics Technical Aspects of Breast Imaging, M Yaffe, et al.,RSNA 1993


Spectral Shaping – K edge filtration
Mo target -- 26 kVp unfiltered spectra
photons/mm 2 x 10 6
Energy, keV
Linear Attenuation Coefficient, Mo filter
μ (cm-1) x 10 3
Energy (keV)
Mo target: 26 kVp and 0.030 mm Mo filter
0.03 mm Mo
x 10 6 photons/mm 2
Energy, keV
Mo target: 26 kVp and 0.025 mm Rh filter
Photon flux added with Rh filter
x 10 6 photons/mm 2
Energy, keV
Slide adapted from J.A. Seibert


Unfiltered Bremsstrahlung Spectrum
Mo target -- 26 kVp unfiltered spectra
photons/mm² x 10⁶
35
30
25
20
15
10
5
0
Characteristic Radiation
Optimum Energies
5
10
15
20
25
30
Energy, keV
Low energy: high dose
High energy: low contrast
Slide courtesy J.A. Seibert

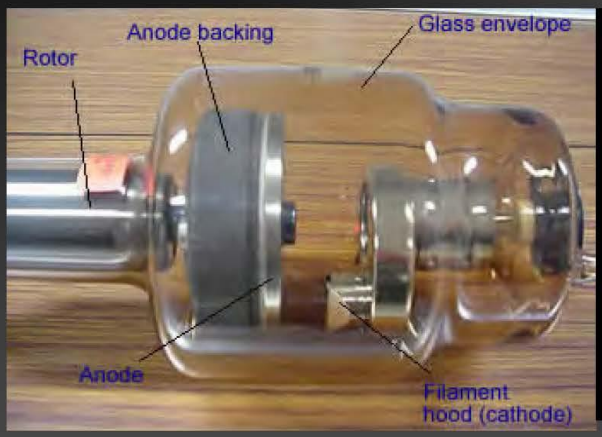

X-ray Beam Geometry
Conventional
Collimator
Half Field
Slide courtesy of J.A. Seibert


Target-Filter Recommendations
Fatty breast up to ~ 4 cm thick
Mo target and 30 micron Mo filter
24 – 26 kVp
Glandular breast ~ 5 to 7 cm
Mo target and 25 micron Rh filter
27 – 31 kVp
Breast thickness > 7 cm
Rh target and 25 micron Rh filter


Heel Effect
Cathode ------- Anode Axis
Chest Wall
Intensity
100%
0%
Cathode
Anode
Target self-absorption reduces the intensity in the cathode to anode direction
Large target angle is needed, > 20⁰ , for full field coverage
Projected focal spot size improves as well

X-Ray Tubes

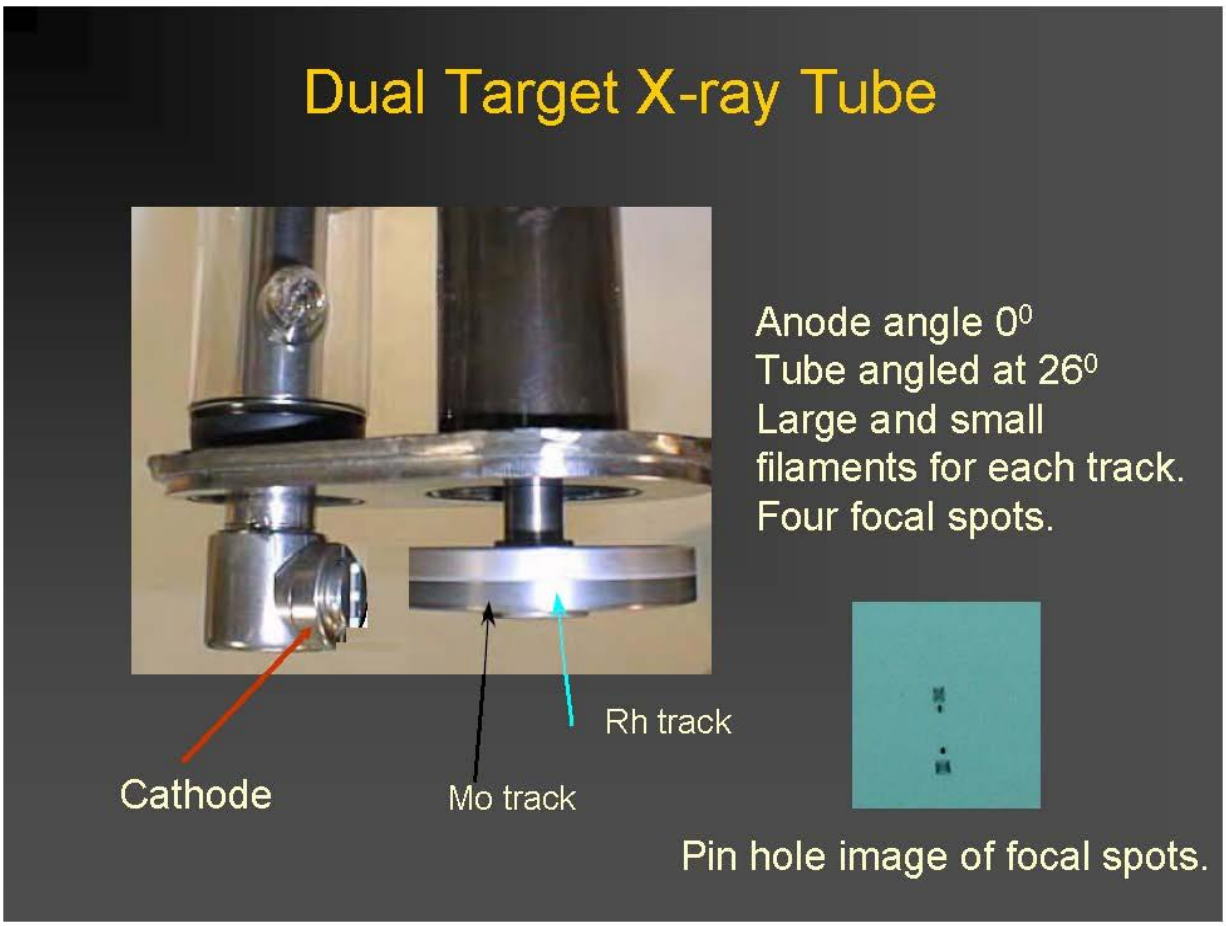
Conventional



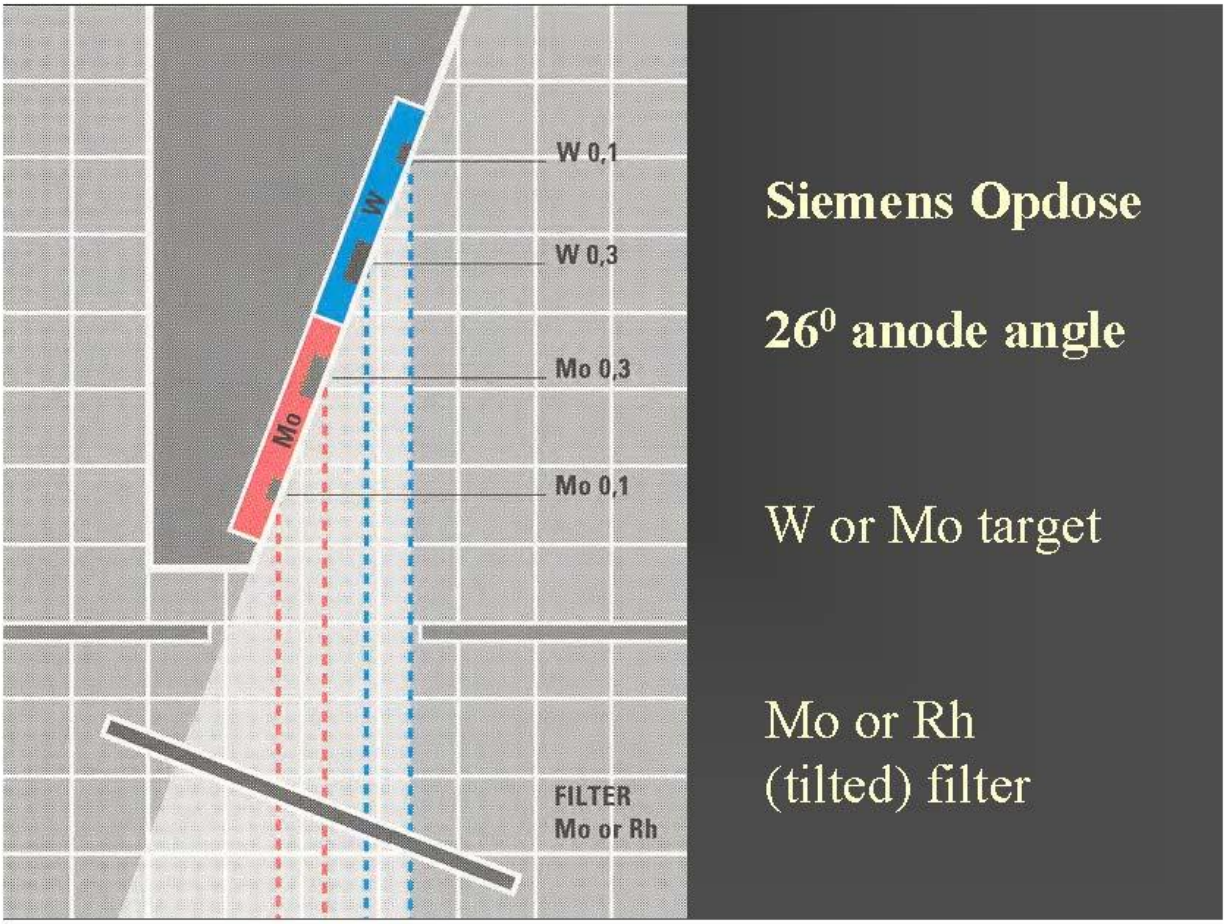
- glass envelope
- tungsten anode
- anode angle ~7^0 to 16^0
- axis of rotation – horizontal
- Al filter for dose reduction

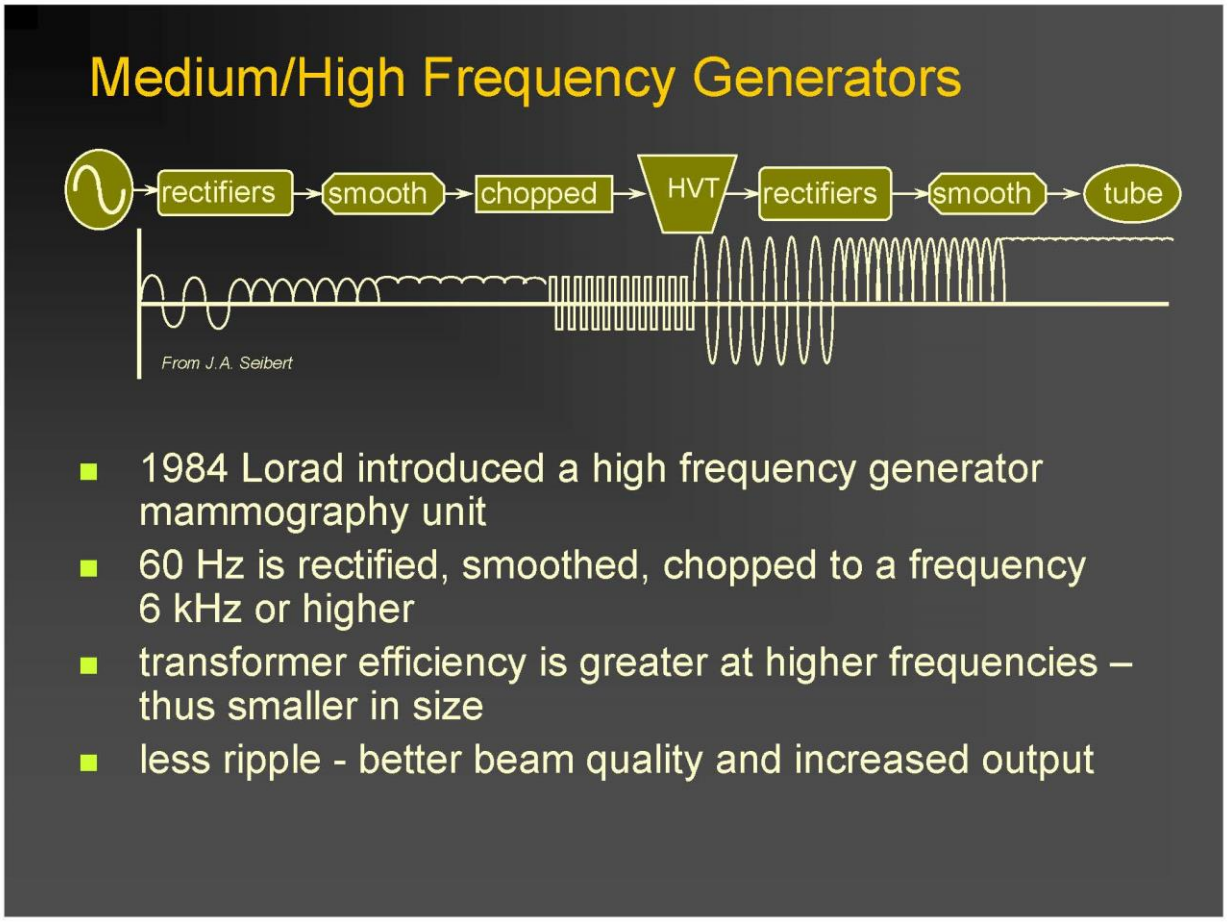
Mammography

- metal tube housing
- grounded Mo, Rh anode
- anode angle 0^0 - tube tilt of 26^0
- axis of rotation ~ vertical
- Mo or Rh filters for spectral shaping


Dual Target X-ray Tube
Anode angle 0⁰
Tube angled at 26⁰
Large and small
filaments for each track.
Four focal spots.
Rh track
Cathode
Mo track
Pin hole image of focal spots.

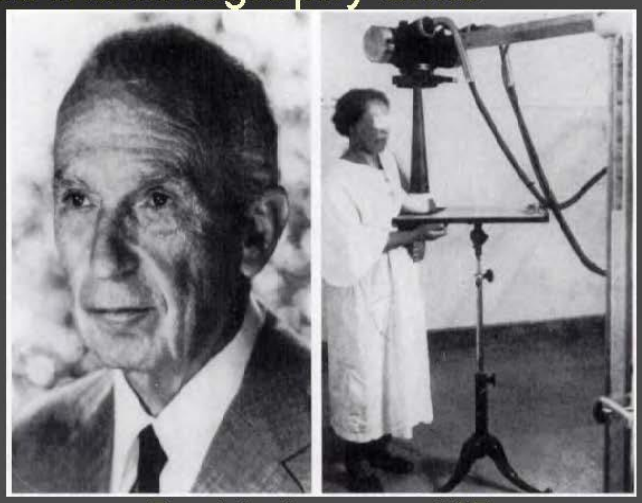

Mammography X-Ray Tube


W 0,1
W 0,3
Mo 0,3
Mo 0,1
W
Mo
FILTER
Mo or Rh
Siemens Opdose
26⁰ anode angle
W or Mo target
Mo or Rh
(tilted) filter

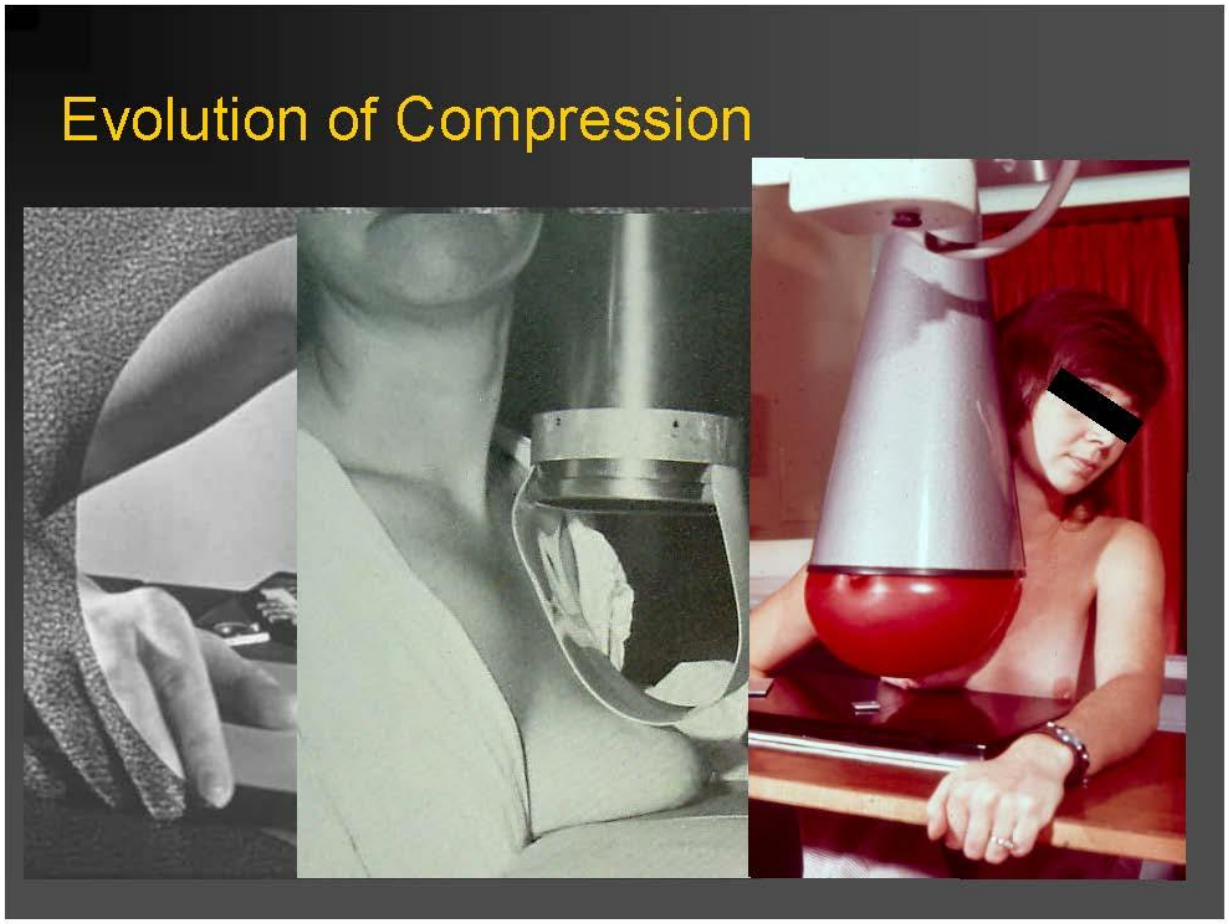

Medium/High Frequency Generators
rectifiers
smooth
chopped
HVT
rectifiers
smooth
tube
From J.A. Seibert
1984 Lorad introduced a high frequency generator mammography unit
60 Hz is rectified, smoothed, chopped to a frequency 6 kHz or higher
transformer efficiency is greater at higher frequencies – thus smaller in size
less ripple - better beam quality and increased output

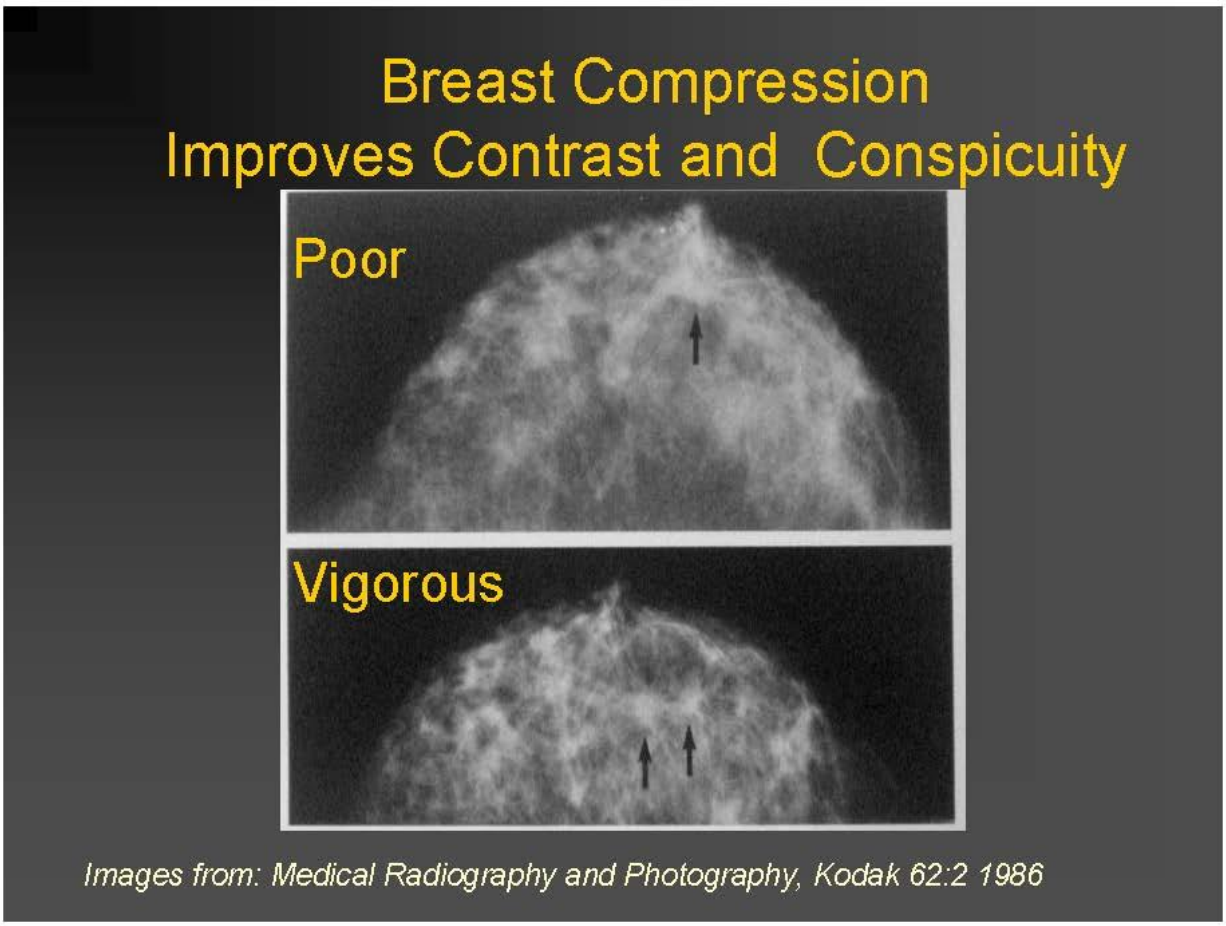
Breast Compression

- 1949 R. Leborgne, Uruguanian radiologist first uses breast compression
- By 1970's compression devices common on dedicated mammography units



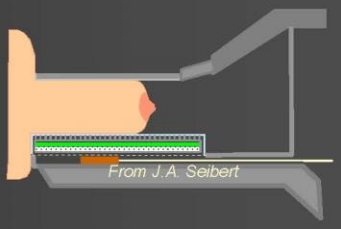
Raul Leborgne, MD


Evolution of Compression

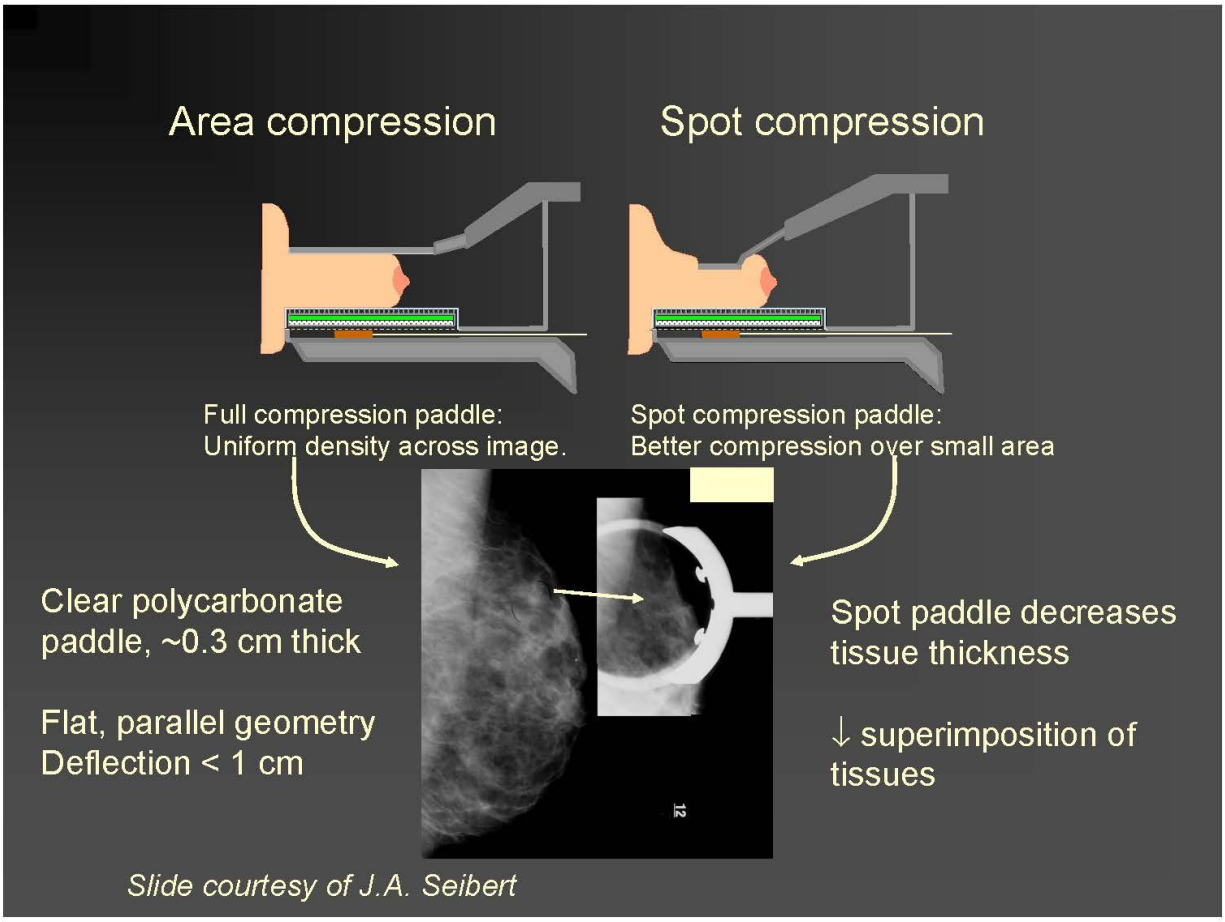

Breast Compression
Improves Contrast and Conspicuity
Poor
Vigorous
Images from: Medical Radiography and Photography, Kodak 62:2 1986

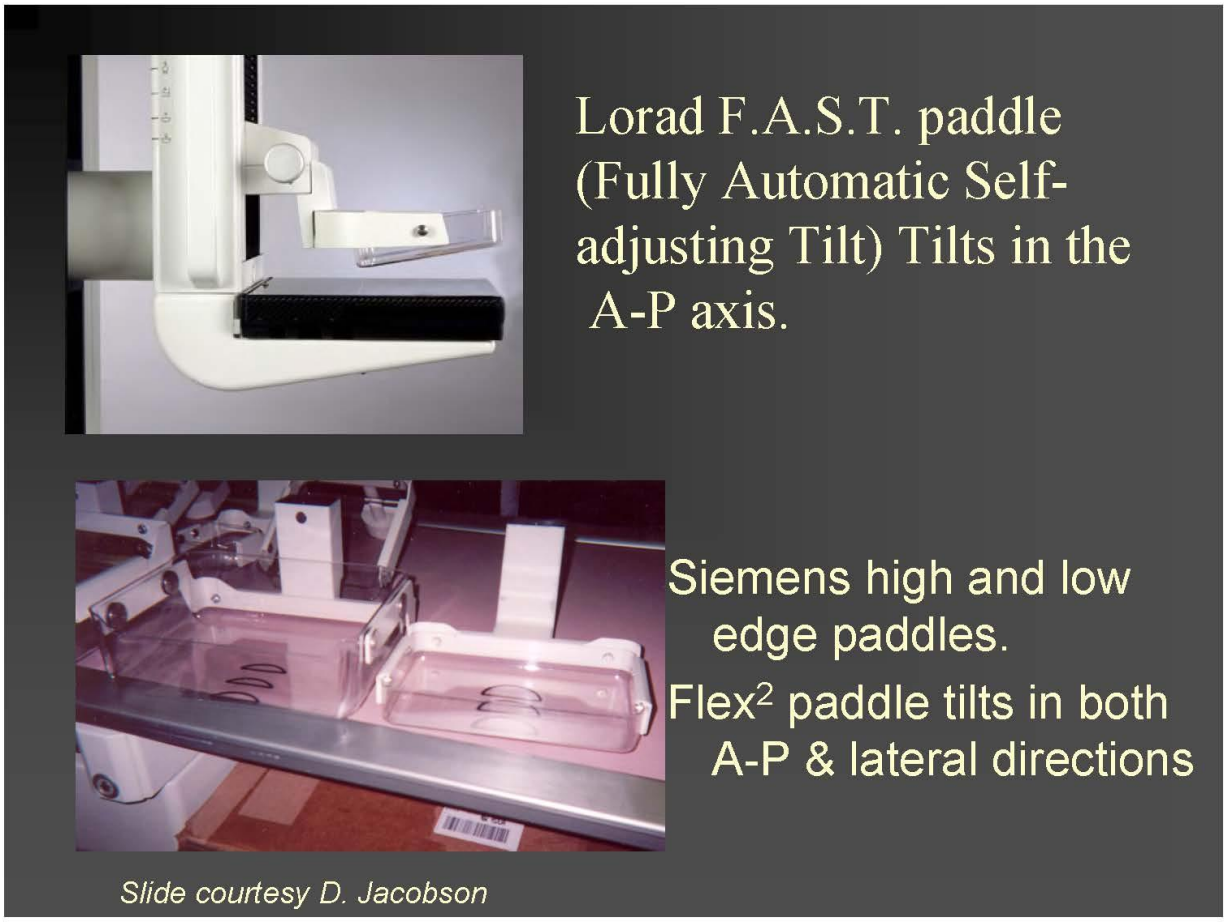
Breast Compression

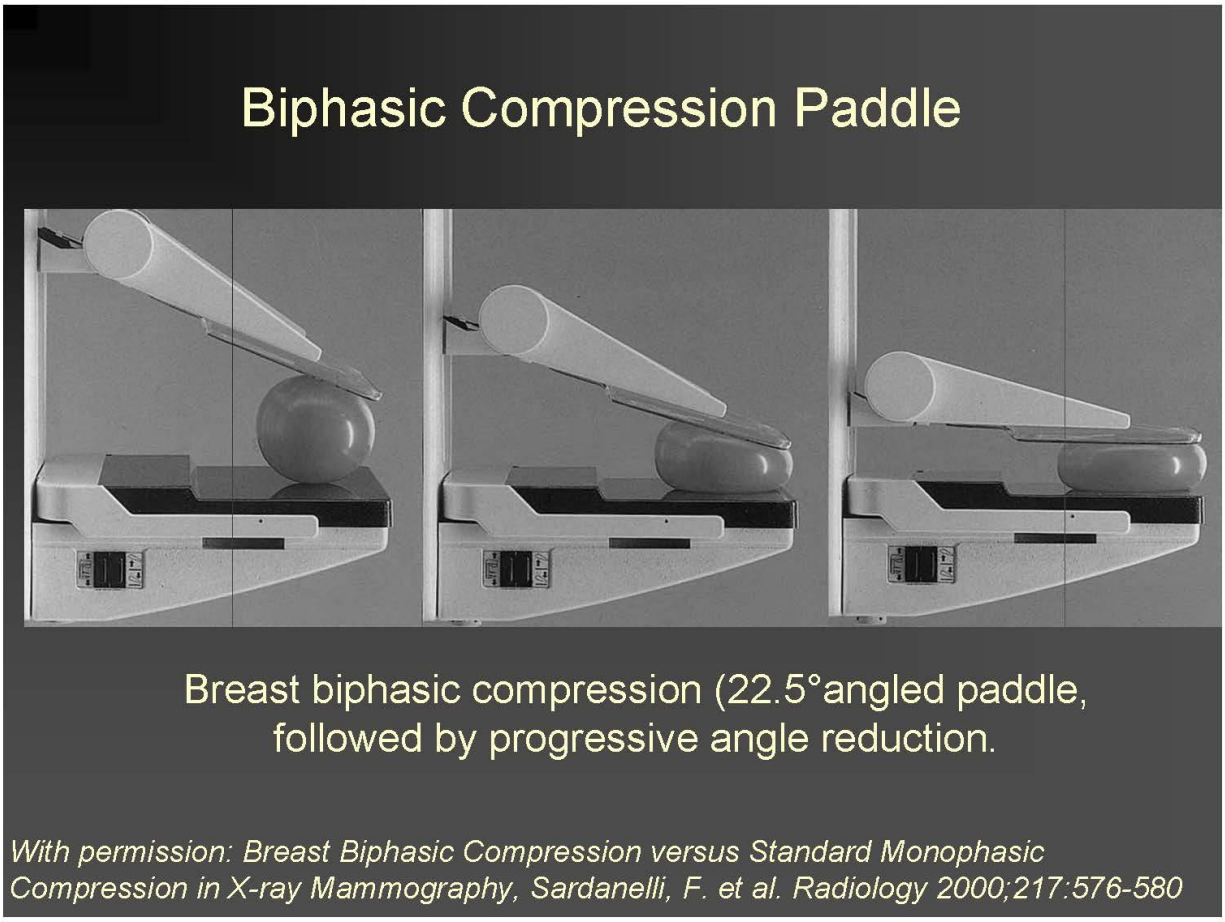
Area compression

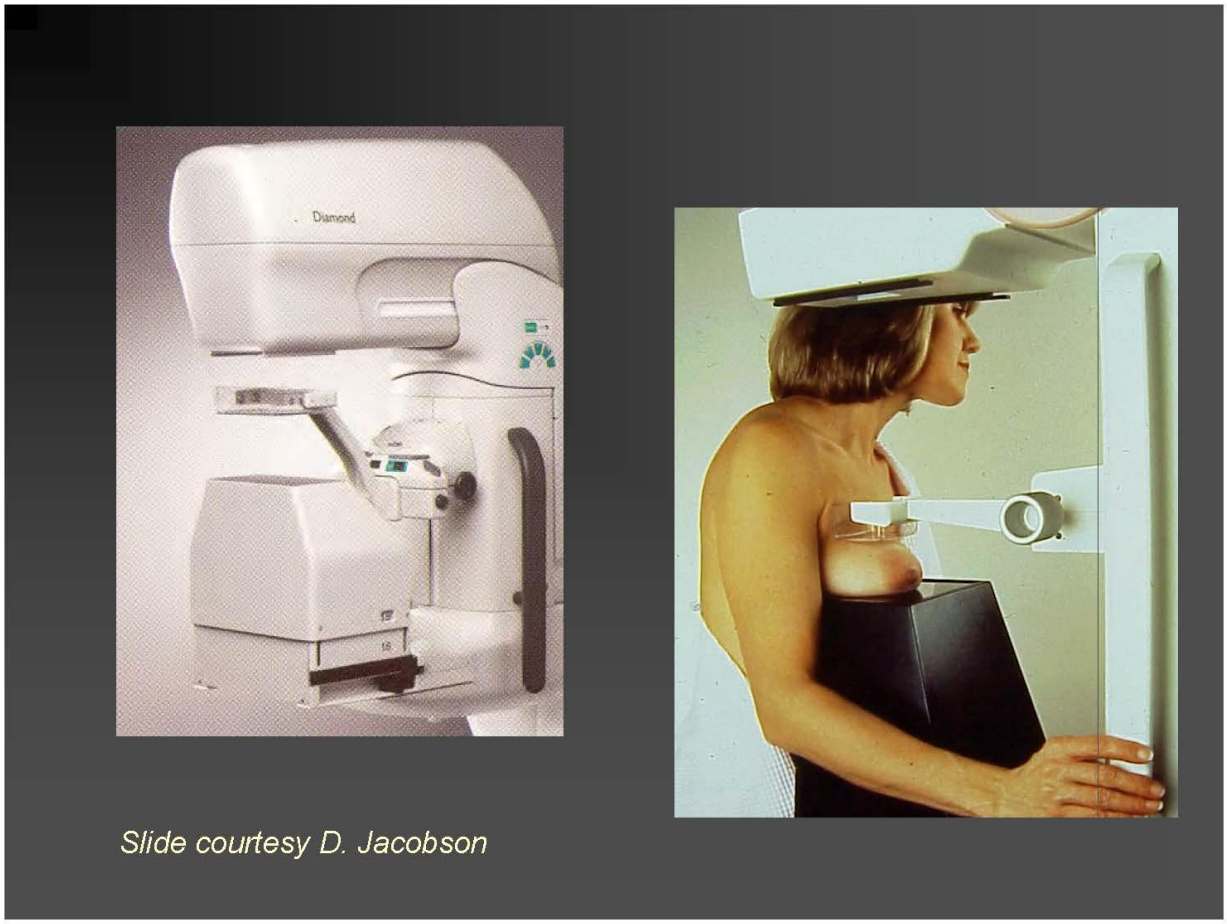


- Reduces breast thickness
  - lowers radiation dose
  - spreads breast tissues apart
  - produces a more uniform thickness
    - allows use of narrow latitude, high contrast film
- Reduces motion and geometric unsharpness
- Reduces x-ray scatter and beam hardening, thus improving contrast


Area compression
Spot compression
Full compression paddle:
Uniform density across image.
Spot compression paddle:
Better compression over small area
Clear polycarbonate paddle, ~0.3 cm thick
Flat, parallel geometry
Deflection < 1 cm
Spot paddle decreases tissue thickness
↓ superimposition of tissues
Slide courtesy of J.A. Seibert

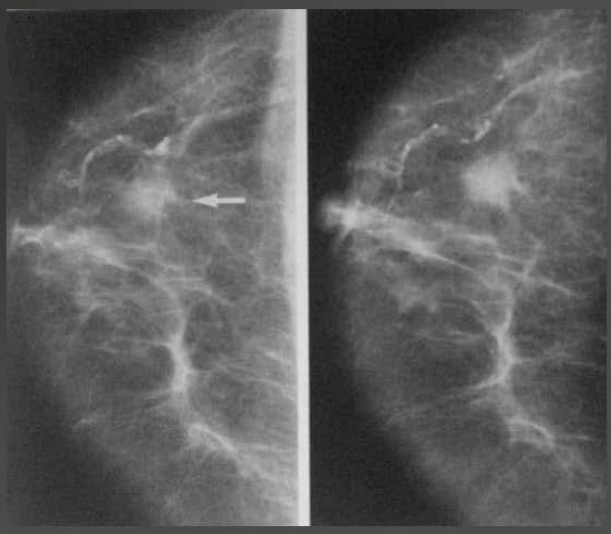

Lorad F.A.S.T. paddle (Fully Automatic Self-adjusting Tilt) Tilts in the A-P axis.
Siemens high and low edge paddles.
Flex2 paddle tilts in both A-P & lateral directions
Slide courtesy D. Jacobson


Biphasic Compression Paddle
Breast biphasic compression (22.5°angled paddle, followed by progressive angle reduction.
With permission: Breast Biphasic Compression versus Standard Monophasic Compression in X-ray Mammography, Sardanelli, F. et al. Radiology 2000;217:576-580


Diamond
Slide courtesy D. Jacobson

Anti-scatter Grids

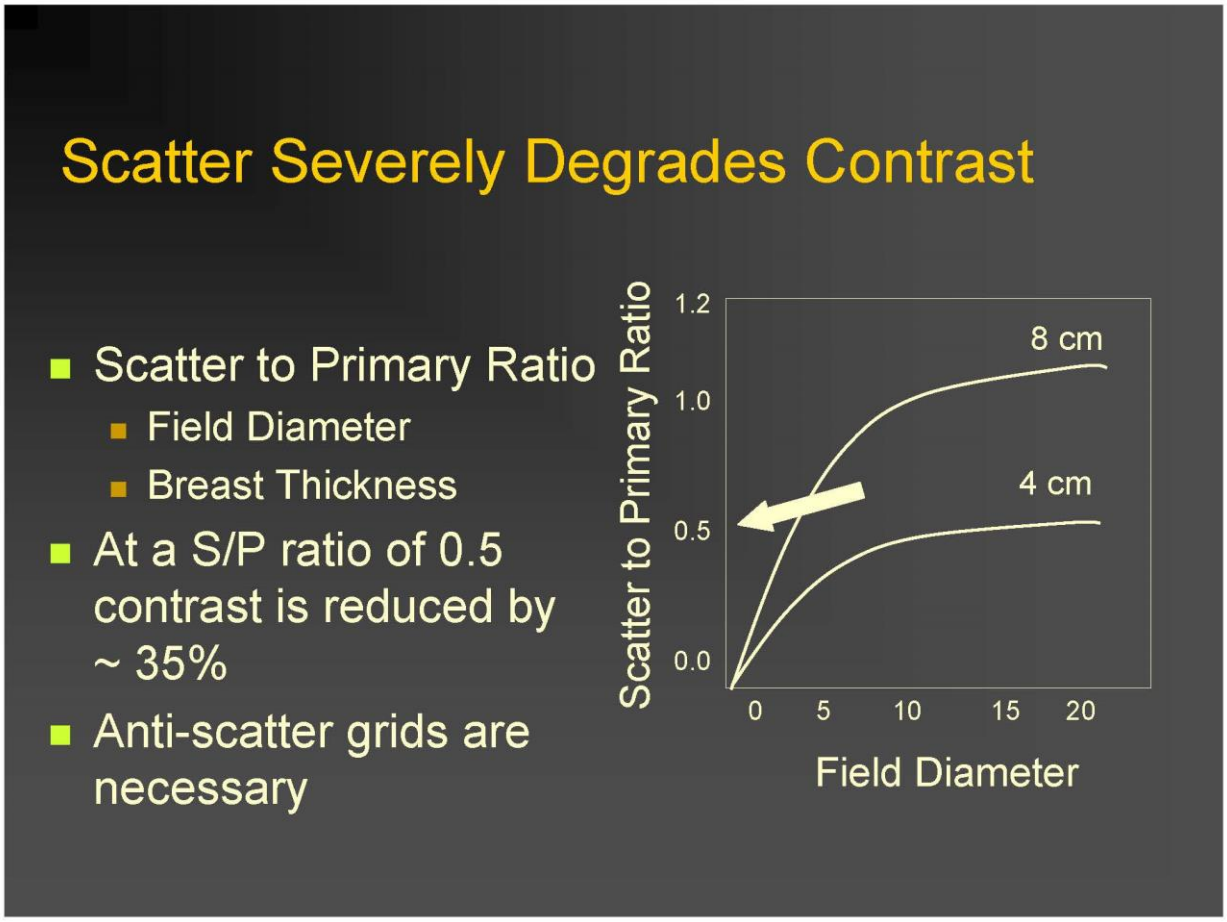
- 1978
  - Philips introduces the Diagnost-U with a moving grid
- 1984
  - Leibel-Flarsheim introduces fine-line stationary grid



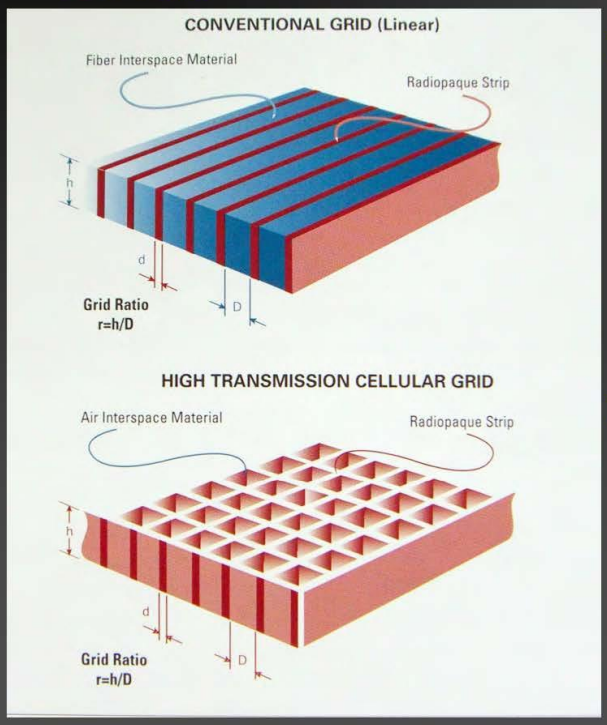
Images from: Medical Radiography and Photography, Kodak 62:2 1986

No grid
26 kVp

With grid
28 kVp

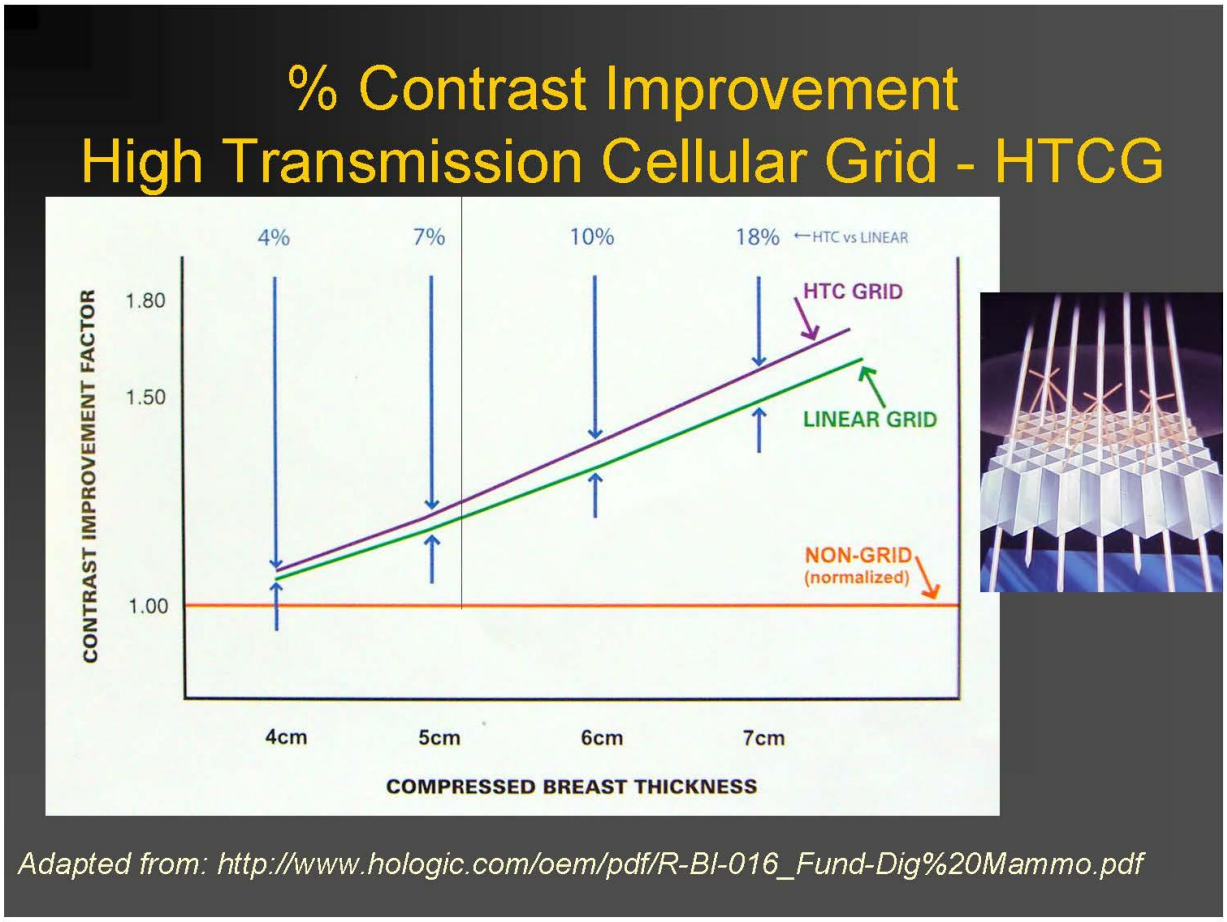

Scatter Severely Degrades Contrast
Scatter to Primary Ratio
Field Diameter
Breast Thickness
At a S/P ratio of 0.5 contrast is reduced by ~ 35%
Anti-scatter grids are necessary
Scatter to Primary Ratio
1.2
1.0
0.5
0.0
8 cm
4 cm
0
5
10
15
20
Field Diameter

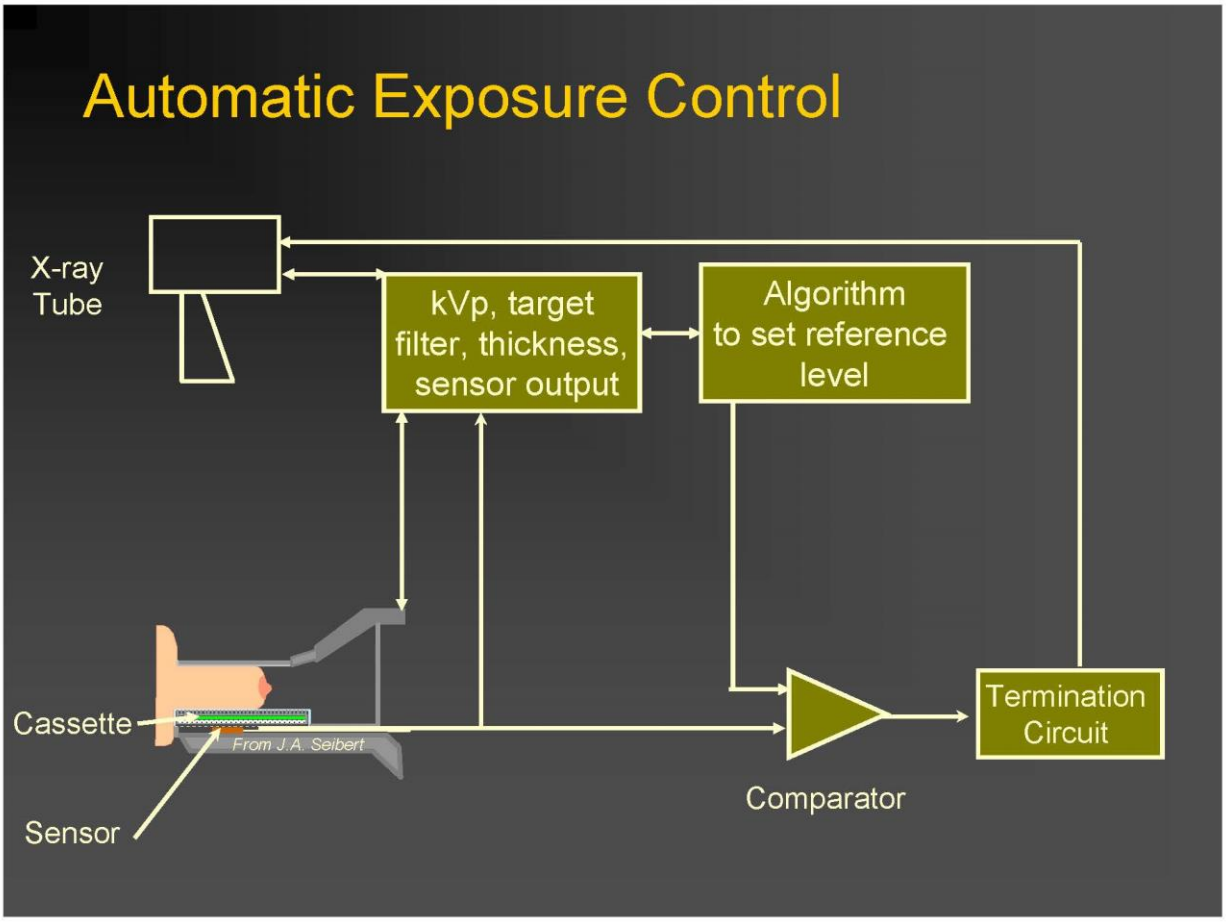
Grids



- Linear grid
  - Ratio: 5:1
  - Frequency > 30 l/cm
  - Wood, paper or carbon fiber inter-space material
  - Moved ~20 lines for blurring
- Cellular grid
  - 15 cells / cm
  - Air inter-space
  - Moved multiple of hole spacing

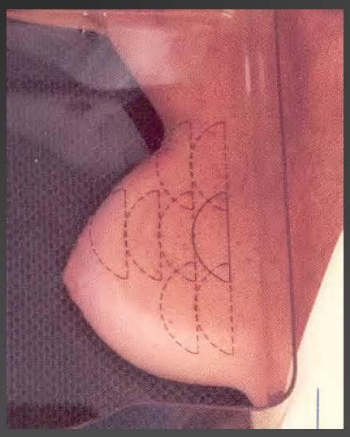
Figure from: http://www.hologic.com/oem/pdf/R-BI-016_Fund-Dig%20Mammo.pdf


% Contrast Improvement
High Transmission Cellular Grid - HTCG
4%
7%
10%
18%
←HTC vs LINEAR
HTC GRID
LINEAR GRID
NON-GRID
(normalized)
CONTRAST IMPROVEMENT FACTOR
1.80
1.50
1.00
4cm
5cm
6cm
7cm
COMPRESSED BREAST THICKNESS
Adapted from: http://www.hologic.com/oem/pdf/R-BI-016_Fund-Dig%20Mammo.pdf

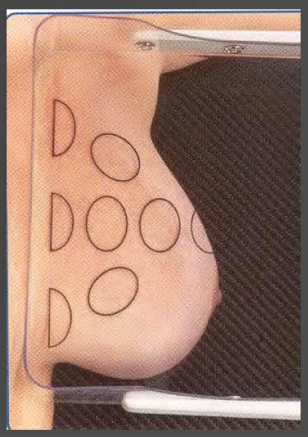

Automatic Exposure Control
X-ray Tube
kVp, target filter, thickness, sensor output
Algorithm to set reference level
Termination Circuit
Cassette
From J.A. Seibert
Sensor
Comparator

Automatic Exposure Control

- AEC sensor is located *underneath* the cassette
  - typical screen exposure is 5 to 10 mR
  - variable sensor position
  - should be under densest tissue



GE Instrumentarium
Vector Point



GE Instrumentarium
Diamond Autopoint

Automatic Exposure Control

- AEC sensor is located *underneath* the cassette
  - typical screen exposure is 5 to 10 mR
  - variable sensor position
  - should be under densest tissue
  - integrated signal is used to terminate the exposure

GE Instrumentarium Diamond Autopoint

AEC Modes of Operation

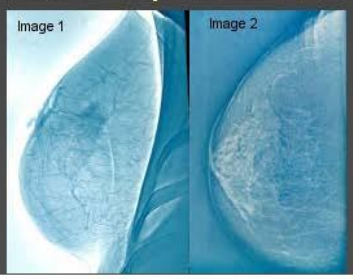
- Auto Time
  - kVp, target/filter chosen by operator
- Auto kVp
  - kVp chosen on basis of breast thickness
- Full Automatic
  - kVp, target/filter chosen by unit
- Siemens – Opdose
  - Breast thickness used to suggest kVp and target/ filter combination
- GE Instrumentarium
  - kVp adjusted during exposure to achieve exposure time of ~2 seconds
- GE DMR
  - Attenuation (100 ms) and breast thickness are used to select kVp and target/filter combination
  - Three algorithms – STD, DOSE and CNT

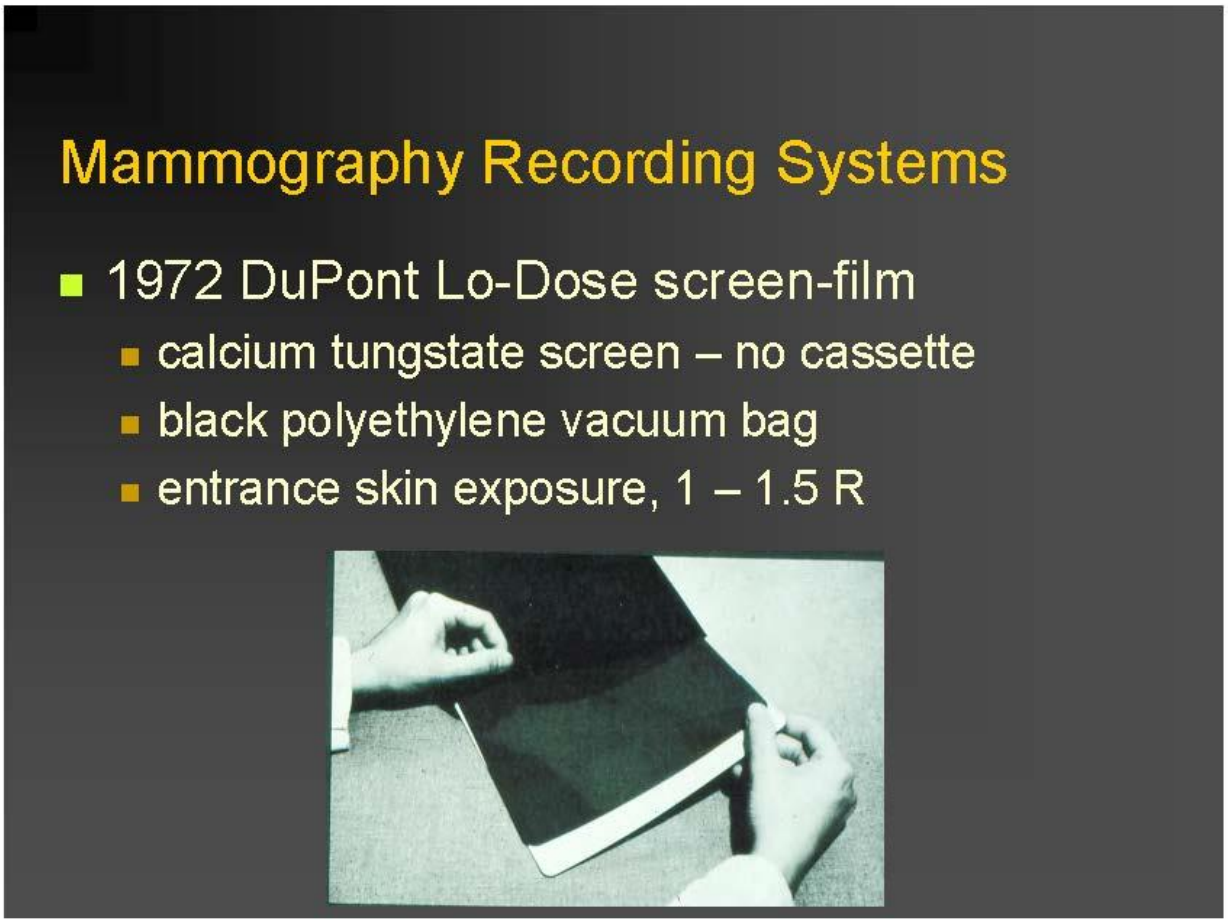
Mammographic Recording Systems

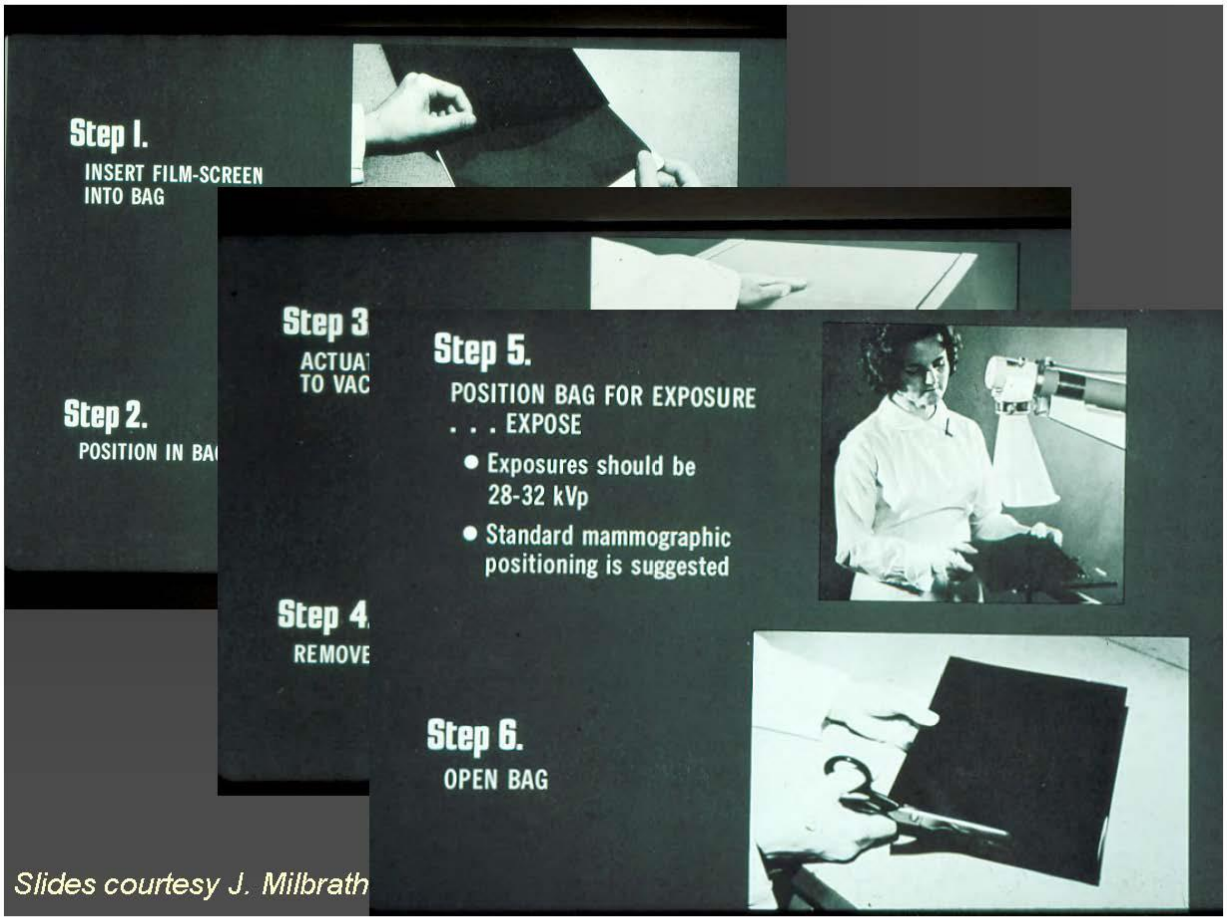
- 1960's non-screen industrial film
  - hand processing – 5 minutes
- 1970 Kodak RP/M non-screen film
  - 90 second processing
  - entrance skin exposure, 3 – 10 R

Mammography Recording Systems

- 1950's non-screen industrial film
- 1970 Kodak RP/M non-screen film
  - 90 second processing
  - entrance skin exposure, 3 – 10 R
- 1971 Xeroradiography
  - blue powder
  - entrance skin exposure, 2 – 4 R




Mammography Recording Systems
1972 DuPont Lo-Dose screen-film
calcium tungstate screen – no cassette
black polyethylene vacuum bag
entrance skin exposure, 1 – 1.5 R

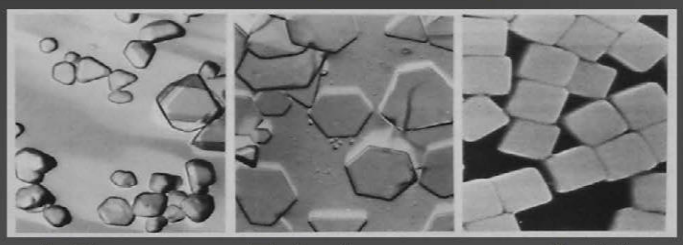

Step I.
INSERT FILM-SCREEN
INTO BAG
Step 2.
POSITION IN BA
Step 3
ACTUA
TO VAC
Step 4
REMOVE
Step 5.
POSITION BAG FOR EXPOSURE
. . . EXPOSE
• Exposures should be 28-32 kVp
• Standard mammographic positioning is suggested
Step 6.
OPEN BAG
Slides courtesy J. Milbrath

Mammography Recording Systems

- 1972 DuPont Lo-Dose screen-film
  - calcium tungstate screen
  - black polyethylene vacuum bag
  - entrance skin exposure, 1 – 1.5 R
- 1976 DuPont Lo-Dose II
  - rare-earth screen, cassette
- 1976 Kodak MinR
  - rare-earth screen, cassette

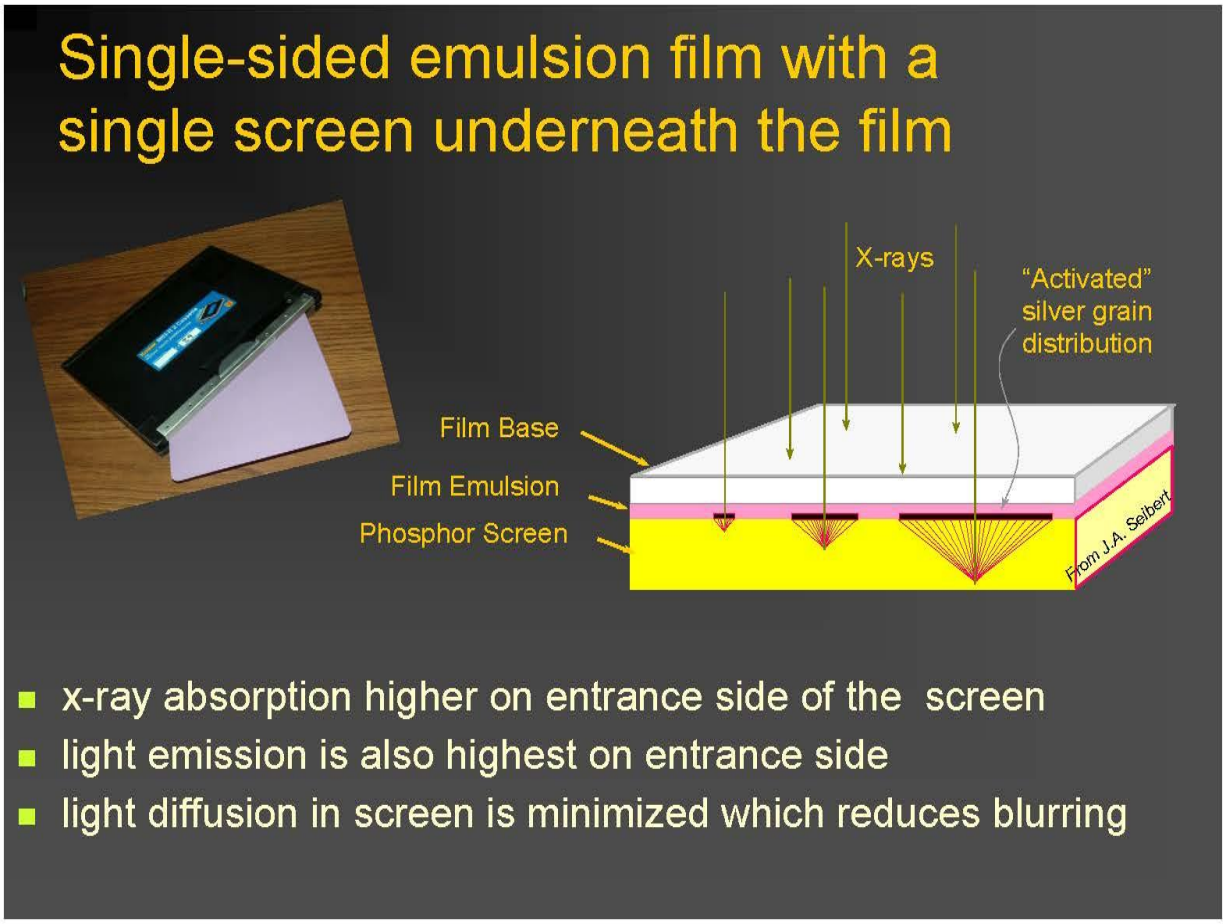
Mammography Recording Systems

- 1983 Kodak Min- R screen-film system
  - gadolinium oxysulfide with orthochromatic film
    - (other rare earth phosphors developed)
  - significant reduction in dose compared to non-screen film
  - current films employ cubic grains



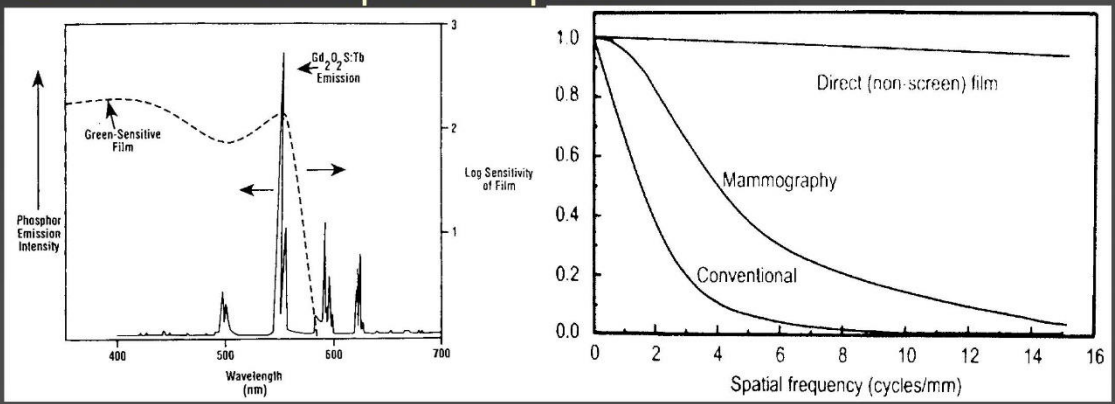
3-D Tabular Cubic

With permission: Medical Physics Publishing, "The Basics of Film Processing in Medical Imaging" by Art Haus and Susan Jaskulski


Single-sided emulsion film with a single screen underneath the film
X-rays
"Activated" silver grain distribution
Film Base
Film Emulsion
Phosphor Screen
From J.A. Seibert
x-ray absorption higher on entrance side of the screen
light emission is also highest on entrance side
light diffusion in screen is minimized which reduces blurring

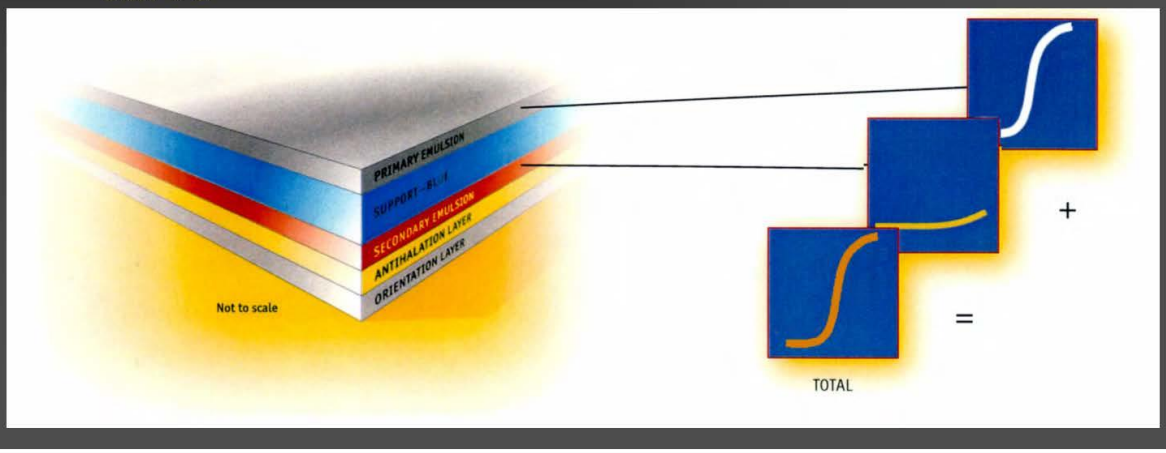
Typical Screen: Gd_2O_2S:Tb

- main emission at 545 nm
  - film spectral sensitivity is matched
- conversion efficiency ~ 15 %
- x-ray absorption of 40 to 60%
- MTF ~ 10% up to 15 lp/mm



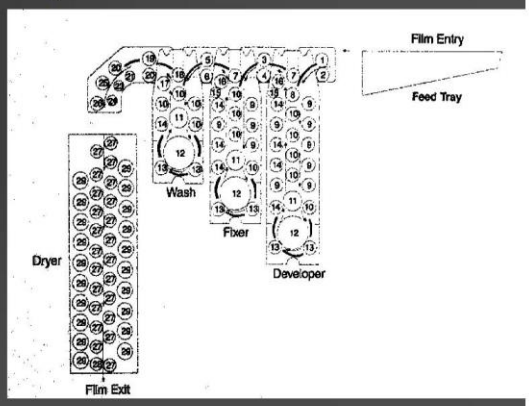
Mammography Recording Systems

- 2003 Kodak Min-R EV
  - Dual emulsion film used with a single screen
  - Asymmetric emulsion design optimizes image quality from toe to shoulder of the sensitometric curve



Film Exposure and Processing

- Latent image formation
  - Light converts AgBr complex into silver ion + electron, creates a sensitivity speck
- Processing (four steps)
  - Developer
    - Chemical amplification ~ 5×10^9
  - Fixer stops development
  - Washing
  - Drying

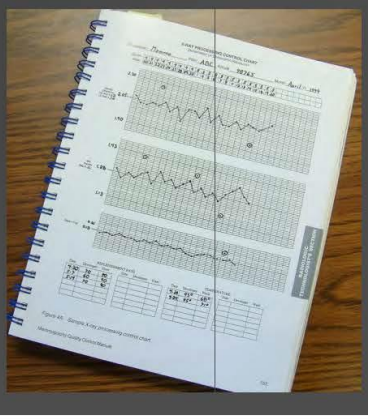


For details see: "The Basics of Film Processing in Medical Imaging" by Art Haus and Susan Jaskulski

Technologist Daily Processor Control

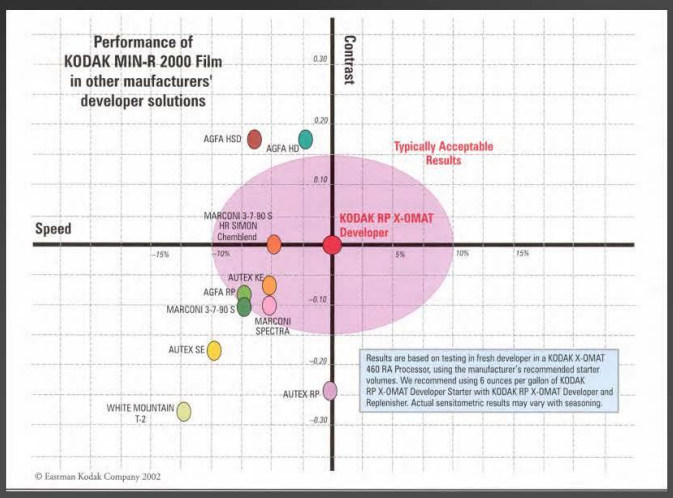
MQSA requires a processor performance test on each day that examinations are performed before any clinical films are processed

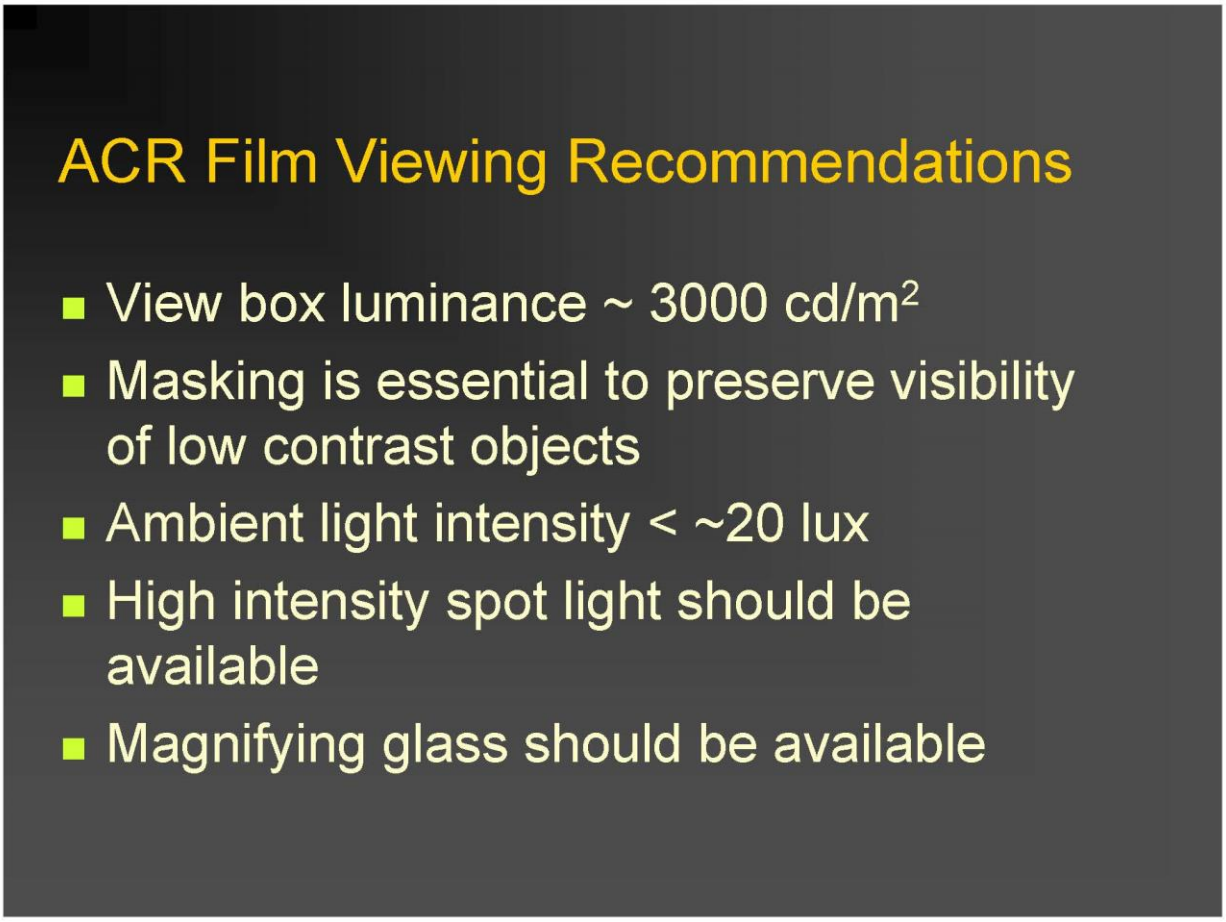
- Density Difference
  - +/- 0.15 DU
- Mid-density
  - +/- 0.15 DU
- Base + Fog
  - +/- 0.03 DU

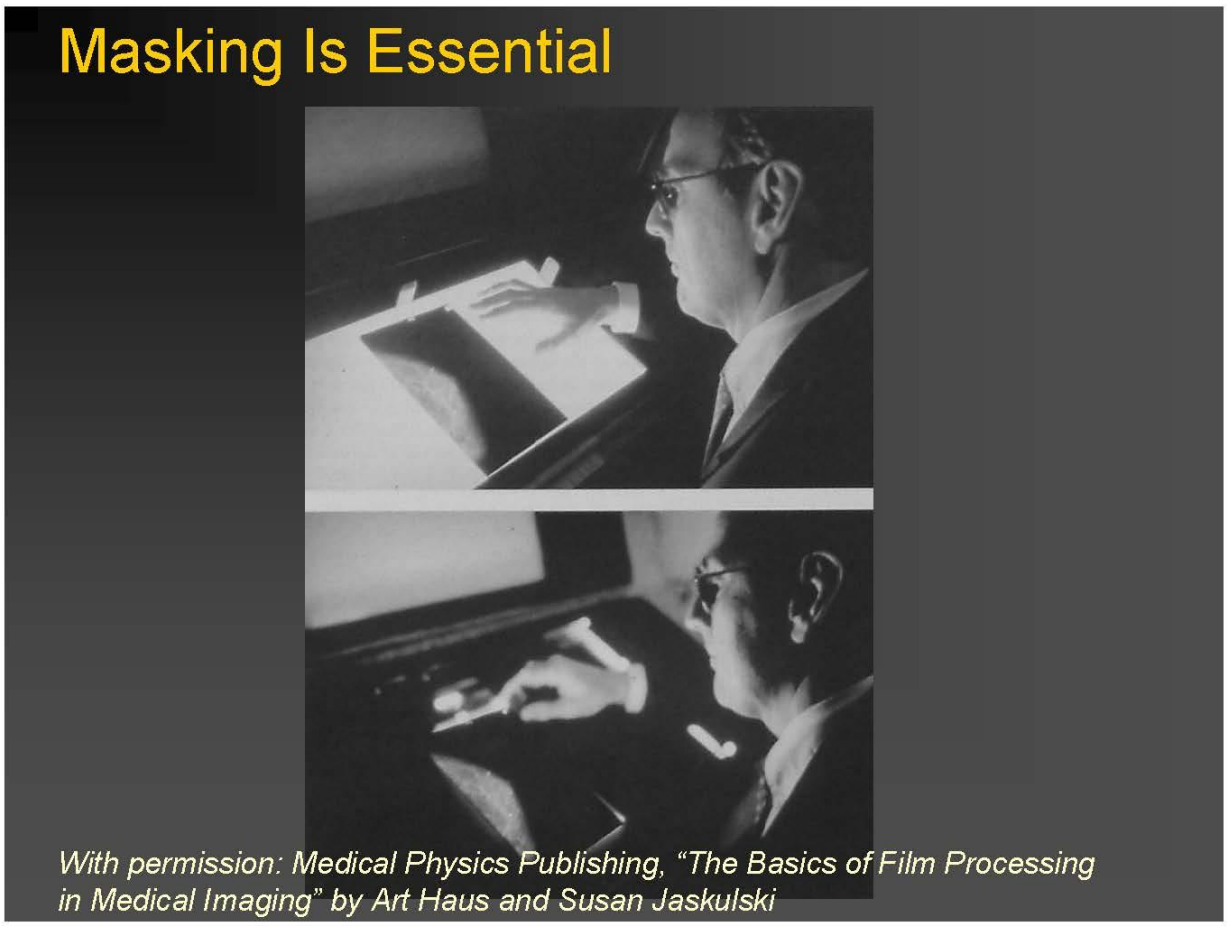


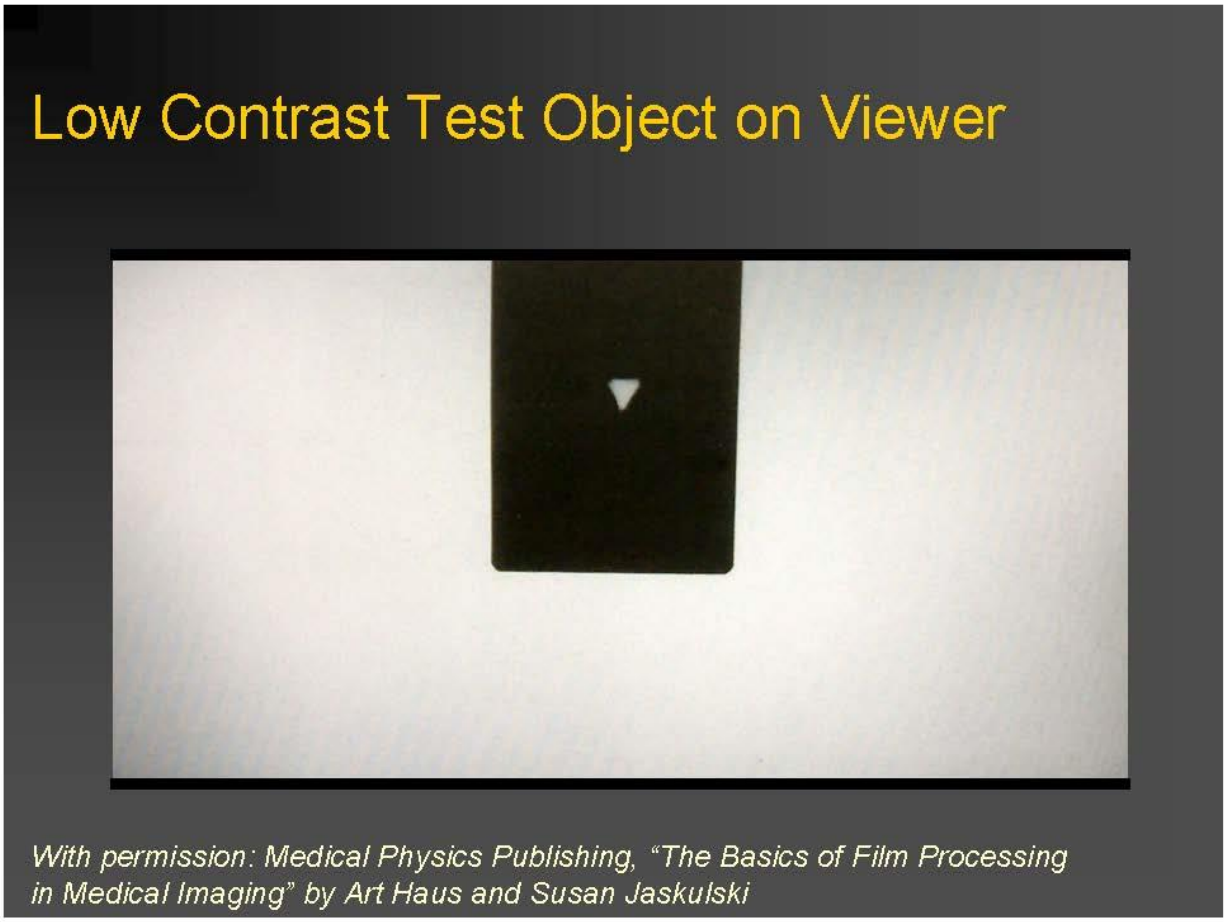
Processing Chemistry

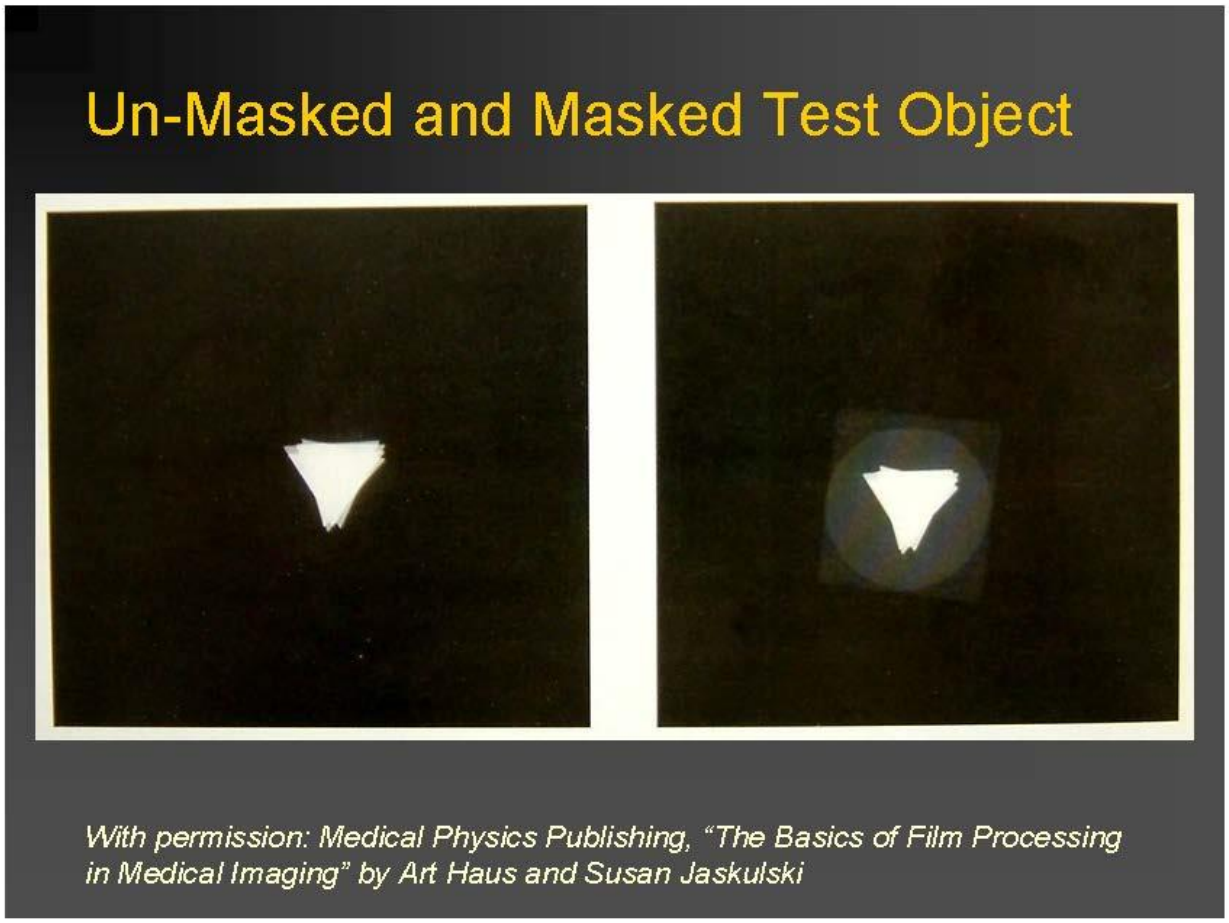
MQSA regulations require a facility to use chemical solutions that are capable of developing the films in a manner equivalent to film manufacturer's specifications.




ACR Film Viewing Recommendations
View box luminance ~ 3000 cd/m2
Masking is essential to preserve visibility of low contrast objects
Ambient light intensity < ~20 lux
High intensity spot light should be available
Magnifying glass should be available


Masking Is Essential
With permission: Medical Physics Publishing, "The Basics of Film Processing in Medical Imaging" by Art Haus and Susan Jaskulski


Low Contrast Test Object on Viewer
With permission: Medical Physics Publishing, "The Basics of Film Processing in Medical Imaging" by Art Haus and Susan Jaskulski


Un-Masked and Masked Test Object
With permission: Medical Physics Publishing, "The Basics of Film Processing in Medical Imaging" by Art Haus and Susan Jaskulski

D_{gN} Conversion (mrad / R)

Mo target / Mo filter

4.5 cm breast: 50% glandular and 50% adipose breast tissue composition

kVp

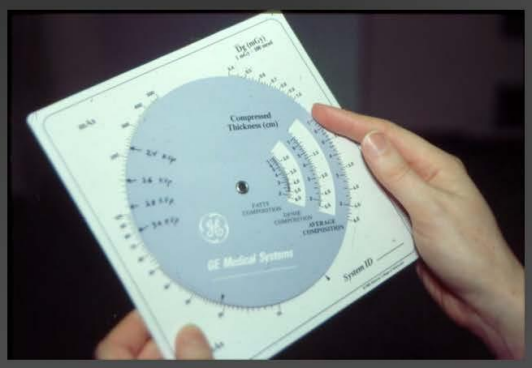
HVL (mm)	25	26	27	28	29	30	31	32
0.25	122							
0.26	126	128						
0.27	130	132	134					
0.28	134	136	138	139				
0.29	139	141	142	143	144			
0.30	143	145	146	147	148	149		
0.31	147	149	150	151	152	153	154	
0.32	151	153	154	155	156	158	159	160
0.33	155	157	158	159	160	162	163	164
0.34	160	161	162	163	164	166	167	168
0.35	164	166	167	168	169	170	171	172
0.36	168	170	171	172	173	174	175	176
0.37		174	175	176	177	178	178	179
0.38			179	180	181	182	182	183
0.39				184	185	186	186	187
0.40					189	190	191	192

ACR QC Manual 1999

Short-cut to Find MGD for MAP Phantom

MGD (mrad) = 0.5 x hvl (mm) x ESE (mR)

Short-cut gives MGD within 2-3% for all target and filters.



D. Jacobson, Radiographic exposure calculator and mammographic dose calculator, Radiology 1992; 182: 578.