THE EVOLUTION OF VISIBILITY IN MEDICAL X-RAY IMAGING
A HISTORICAL PERSPECTIVE

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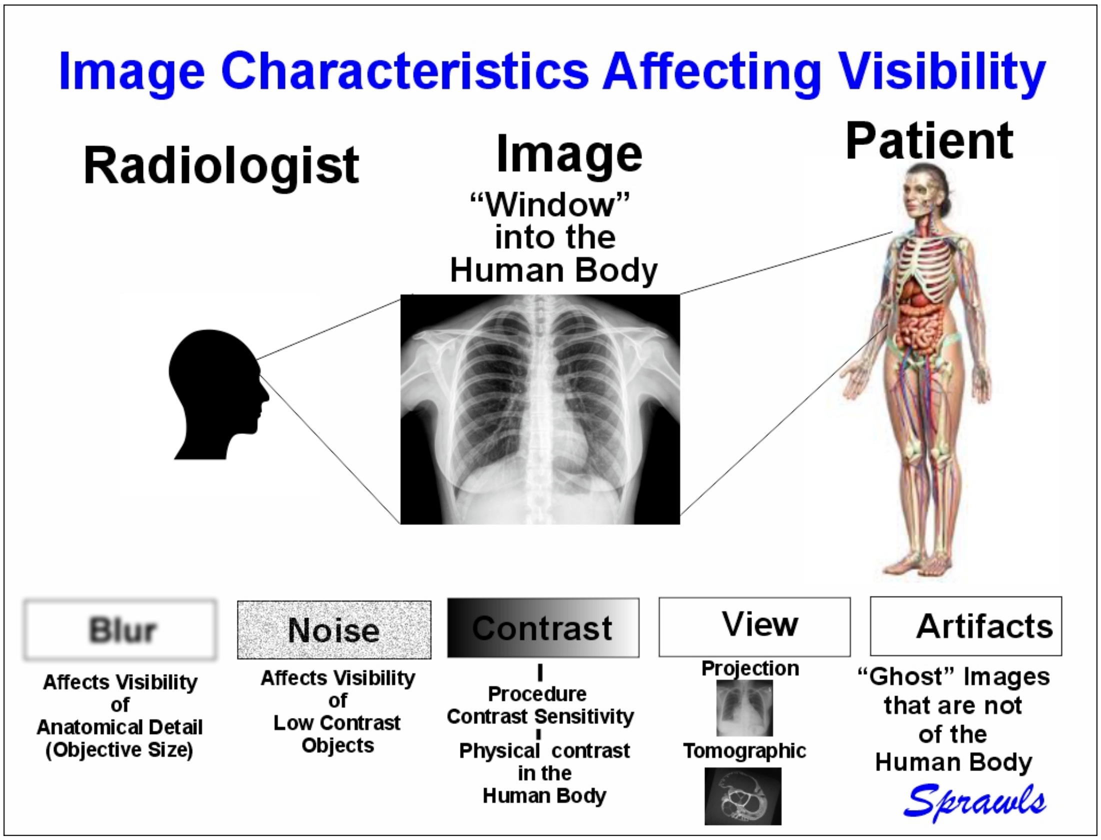
I. INTRODUCTION



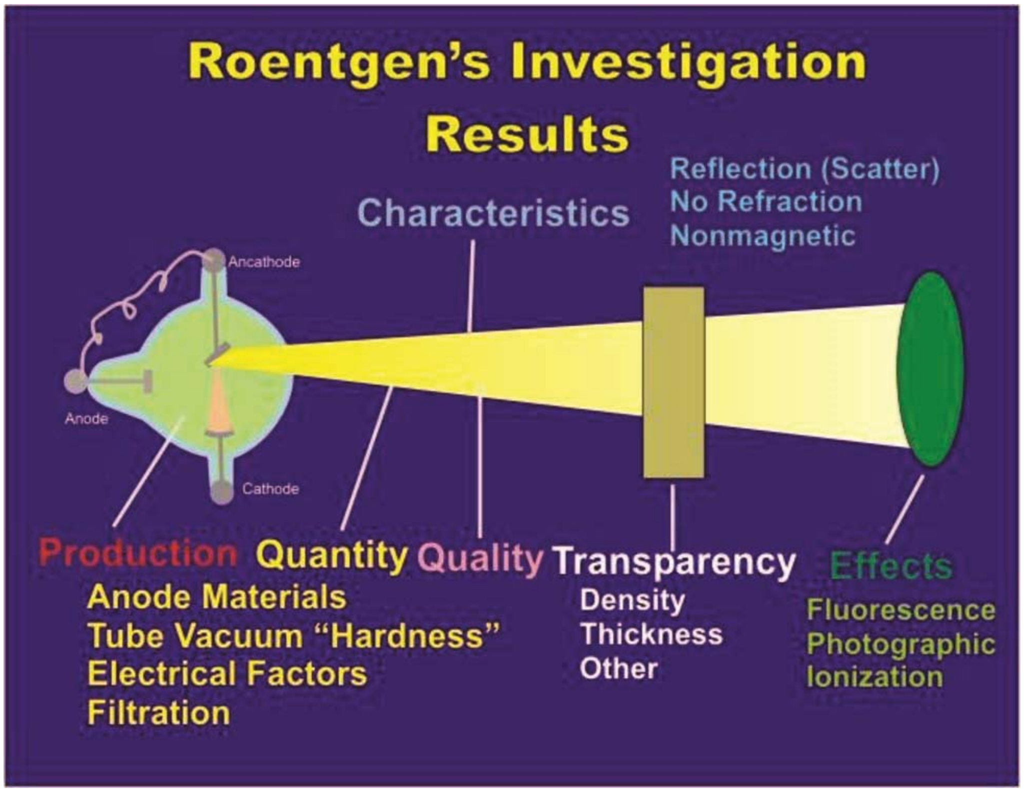
Throughout the course of history, the examination of the human body for diagnosing and treating diseases and injuries was limited to the exterior of the body, except for highly invasive and painful surgeries. This changed in1885 when a physicist, Dr. Wilhelm Roentgen, extended human vision into the human body with the discovery and extensive research on the characteristics of a "New Kind of Radiation" soon to become known as X-rays or Roentgen Radiation.

It was the *visibility* of the internal human body that was to change the course of medicine and become the foundation of the major medical specialty known as Radiology. Roentgenology, or Medical Imaging. The first images produced by. Dr. Roentgen introduced this possibility to the world where of the bones in a hand. They were visible because they were both large and of a different composition (calcium) compared to the surrounding soft tissue, a form of physical contrast.

Visibility, that is the ability to see a specific object or condition with an image depends on a combination of physical characteristics of the image and the imaging procedure as identified above. For well over a century, physicists, often along with engineers and physicians, have invented and developed medical imaging technology and techniques to increase visibility to a much larger range of structures, objects, and conditions in the human body…not just large bones. These developments have in various ways addressed each of the image characteristics that determine and often limit visibility within the body.

II. A NEW KIND OF RADIATION

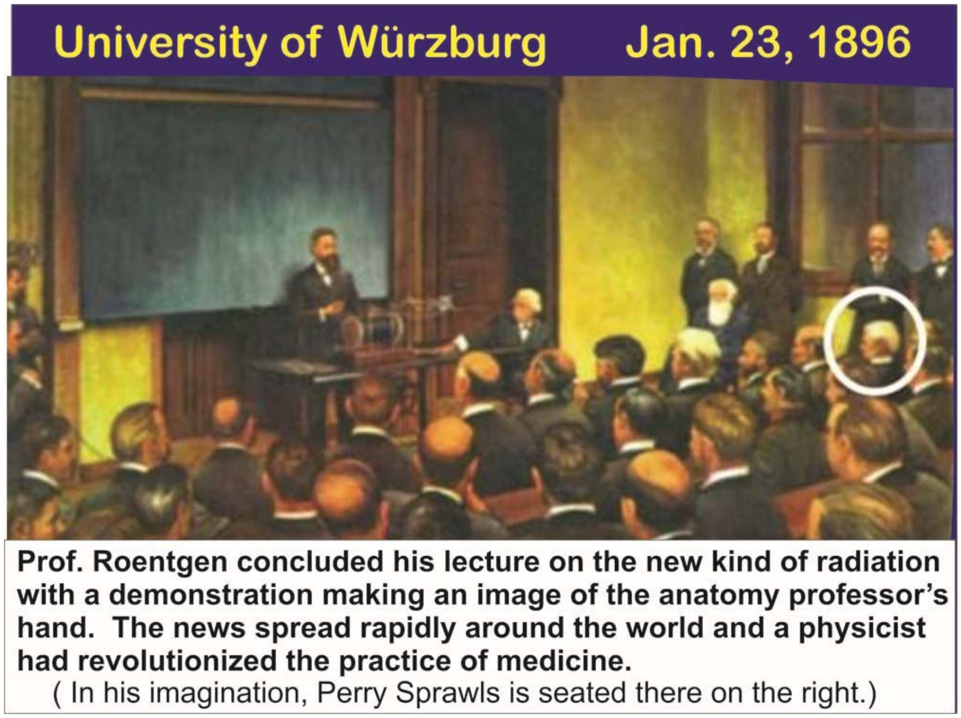
It was not just the discovery of "A New Kind of Radiation" that could penetrate the human body and produce shadow images of the bones that was Roentgen's evolutionary contribution to medicine. It was his extensive research determining the physical characteristics of the radiation summarized here that provided a foundation for physicists, engineers, and other medical professionals to soon begin the development of equipment and imaging methods that would extending the visibility to much more of the body, not just large bones.



The description of this research by Roentgen with illustrations added by Sprawls can be viewed here:

ROENTGEN'S INVESTIGATION DETERMINING THE CHARACTERISTICS OF X-RADIATION
P. Sprawls. MEDICAL PHYSICS INTERNATIONAL Journal, vol.2, No.2, 2014
http://www.mpijournal.org/pdf/2014-02/MPI-2014-02-p435.pdf

Roentgen published the results of his research in several articles (referenced in the above online article) but it was his presentation on January 23.1896 that introduces X-ray imaging for medical purposes to the world.



III. Biological effects, risk, and limitations

It was not recognized for some time after the discovery of new kind of radiation, X-rays, that it could interact with and have a variety of biological effects on human tissue…both good and bad. The good effects were to become the foundation of radiation therapy for treating cancer. Unfortunately, there were also bad or undesirable effects that could produce cancer and other determinants to humans, including death. The impact was on both patients and the scientists and medical professionals that worked with the radiation, but in different ways.

Radiation Workers:

It was the professionals working with the radiation over extended periods of time that received lethal exposures. See:

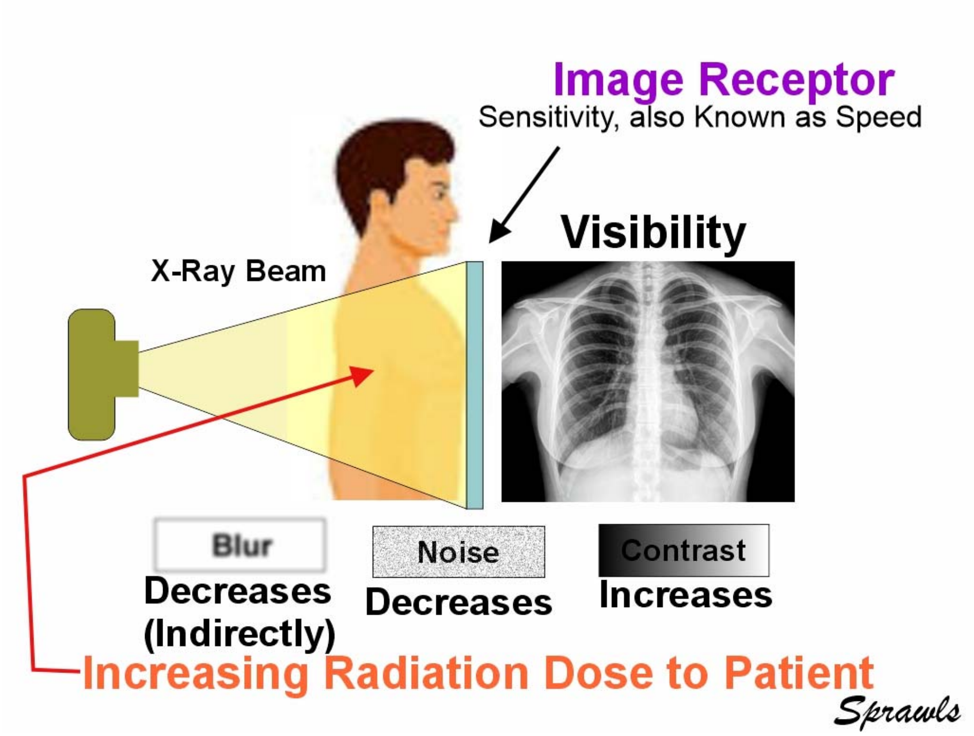
Monument to The X-Ray And Radium Martyrs Of All Nations on the web at:

http://www.mpijournal.org/pdf/2022-SI-08/MPI-2022-SI-08-p1020.pdf.

Patients:

The concern for patients undergoing x-ray imaging procedures was that even though they are exposed to relatively low levels of radiation there is the possibility of increasing the risk or probability of cancer or undesirable genetic effects. These generally have a stochastic relationship to radiation exposure levels without established safe thresholds. Therefore, the effort is to keep the exposure as low as possible to minimize the risk, not to meet some established safe threshold.

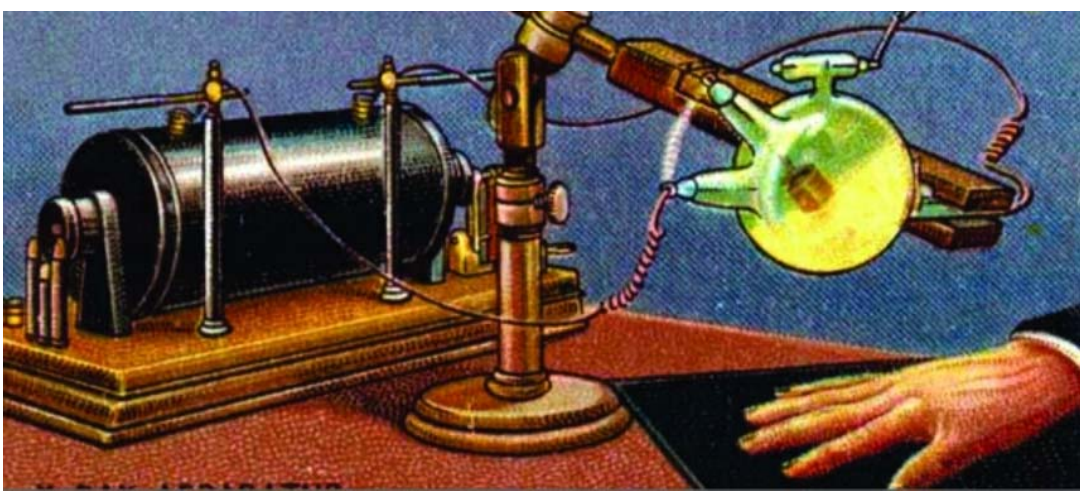
The issue is that reducing the radiation exposure to a patient also reduces the radiation that forms the image and can adversely affect three of the image characteristics that determine visibility as illustrated here.



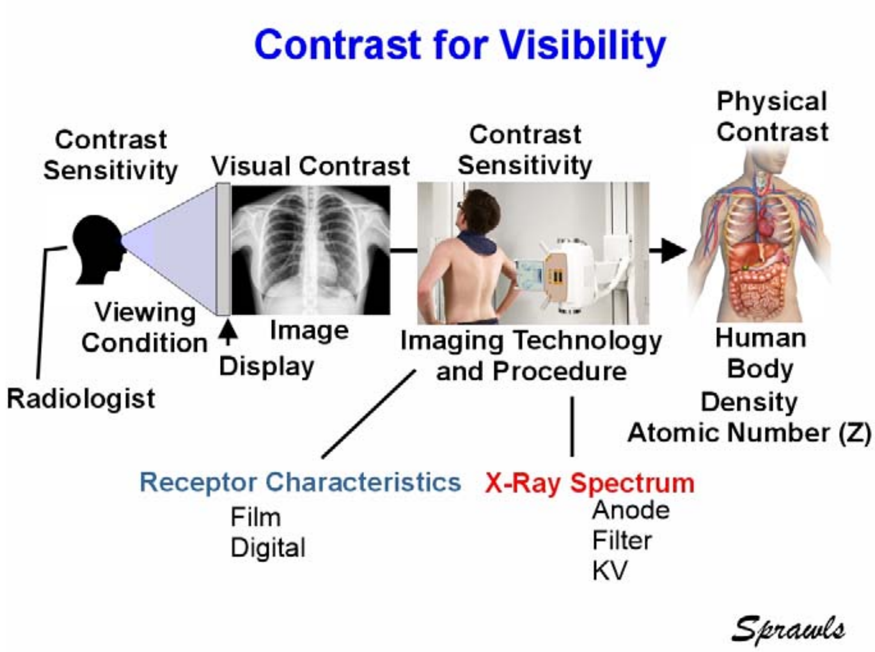
In radiography or general X-ray imaging, as illustrated here, the human body absorbs a major fraction of the radiation in comparison to radiation absorbed by the receptor which determines the characteristic and quality of the image. To increase the exposure to the receptor to improve visibility will result in increased exposure to the patient and presumed increase in risk to cancer and genetic mutations.

IV. In the beginning

At the time of Roentgen's creation of X-ray imaging and its medical applications, the equipment had not been developed for imaging. It was a collection of partially evacuated glass tubes and various high-voltage electrical sources used in physics departments and laboratories for experiments and demonstrations…that just happen to produce X-rays.



V. Contrast

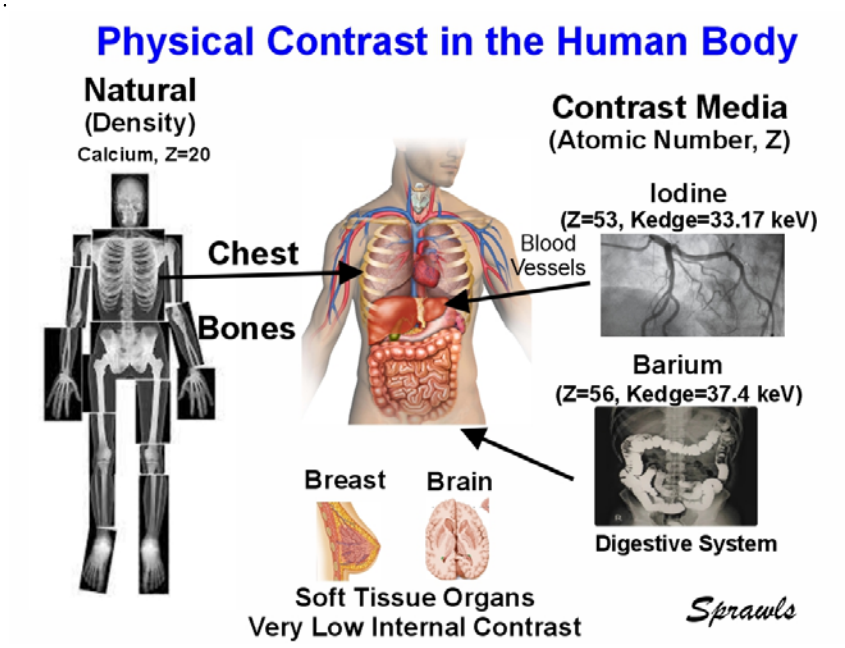


Contrast is the fundamental requirement for *visibility*. An object will only be visible if it has contrast or is physically different from its surrounding area. Then, this physical contrast must be transformed into optical or visible light contrast in an image and then displayed in appropriate conditions so that it is visible to a human, typically a radiologist who can use the visibility of the interior of the body to detect and diagnose diseases and other pathological conditions. As illustrated, the transfer of the physical contrast in the body to perceived contrast by the radiologist is a multi-step and complex process.

The *evolution of visibility* to include a greater range of objects and conditions in the body has resulted from a series of inventions and developments for each of these steps which will now be considered.

Physical Contrast in the Body:

The only objects or conditions that will be visible are those that have some form of *physical contrast* in relation to the surrounding anatomy.



The physical contrast must be one, or both, of the characteristics that control X-ray attenuation, that is density or atomic number (Z). The inherent, or naturally occurring contrast in the body is physical density.

Viewing the Skeleton:

Bones are denser than soft tissues. The higher atomic number of calcium (Z=20) gives bone and effective atomic number (Z=13.8) compared to the effective atomic number of soft tissue (Z=7.4), about the same as water, also contributes to some difference in x-ray attenuation and contrast. Soon after the announcement and demonstration by Roentgen in 1896 physicists around the world who had the tubes and high-voltage sources began imaging bones, sometimes along with medical doctors, and diagnosing and evaluating broken bones…and the practice of medical x-ray was established and changing the world.

The Thoracic Cavity (Chest) Comes into View

Exploring the human body with this new and revolutionary "extension of human vision" was soon underway…especially at first with fluorescent screens (fluoroscopes) to view the images. Now moving past just the bones, it was discovered that the chest cavity and its content was now visible. It was because the lungs partially filled with low-density air provided an excellent background for many of the denser items including cancers and other diseases (tuberculosis), buildup of fluids, the heart, ribs, and much more. The X-ray *image of the chest* was to become the most frequently and routinely performed medical image because of the valuable clinical information it can provide.

Extending Visibility with Contrast Media:

Most of the anatomical systems, other than the skeletal and thoracic, consist of soft tissues and fluids that do not have sufficient variation in density or atomic number to be visible with x-ray imaging. This challenge was met by temporally administering substances, contrast media, that have higher x-ray attenuations because of their specific atomic numbers. Iodine (Z=53) for cardiovascular and urinary system vessels and barium (Z=56) for the digestive system. It is physical, not chemical, characteristics that are significant. Their x-ray attenuation K-edge peaks are in the mid 30 keV range that corresponds to the maximum intensity of a properly adjusted X-ray beam spectrum…more about that later.

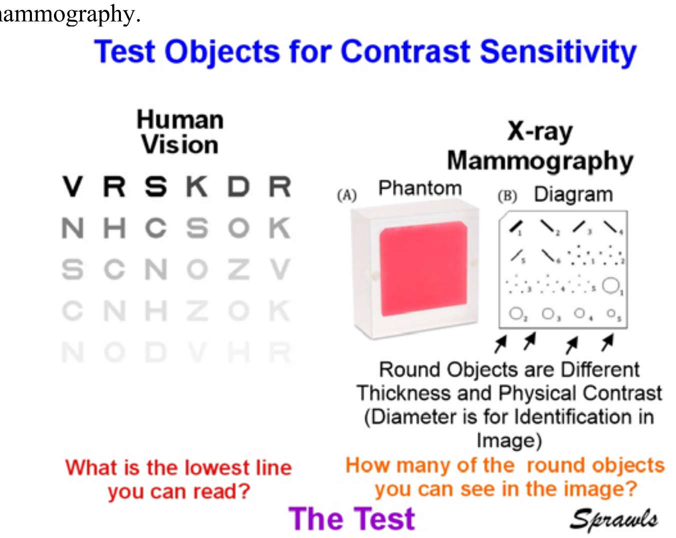
Soft Tissue Contrast:

A continuing challenge to x-ray imaging, and visibility, is that the soft tissues within the various organs, even though they are anatomically and functionally different, do not have the necessary density or atomic number differences to provide contrast for visibility with conventional x-ray imaging methods. These include the female breast and the brain, which is enclosed in a dense skull. These remained invisible for many years until special imaging methods were developed for each and will be considered later.

Imaging Procedure Contrast Sensitivity

Contrast Sensitivity is the characteristic of an imaging process that determines the *range of visibility* in relation to the physical contrast of objects. Specifically, it determines the lowest physical contrast that will be visible. It applies to virtually all imaging processes, including human vision.

Various test objects, sometimes known as phantoms, are used to test or evaluate contrast sensitivity. Two are illustrated here. These tests provide a measure of *relative contrast sensitivity* that are compared to established standards or reference levels for both humans and mammography.



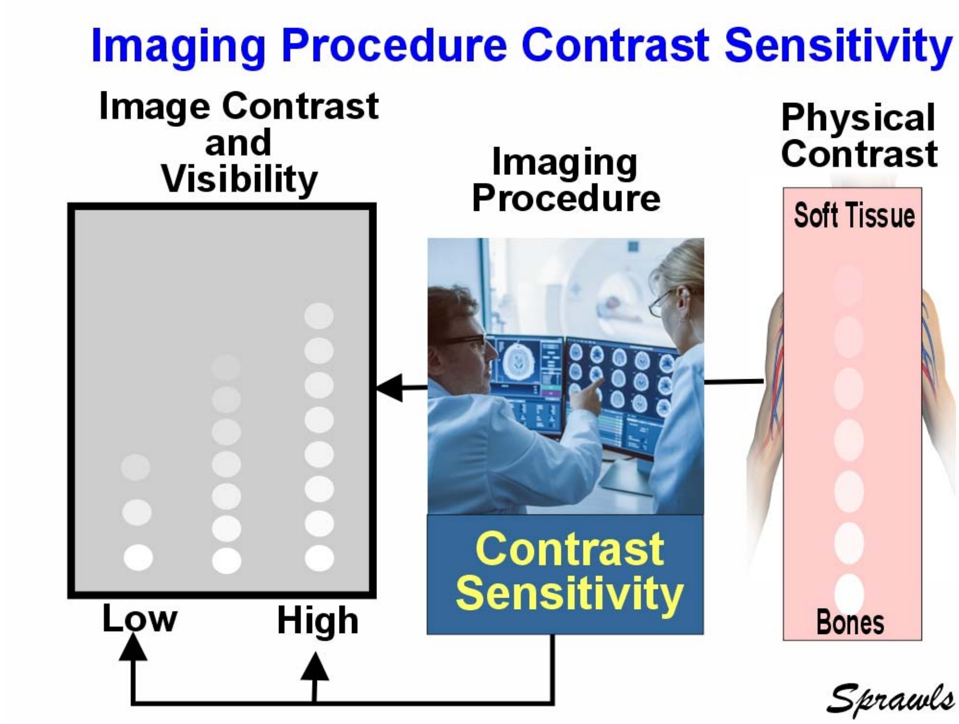
For human vision the test is performed by a physician, usually an ophthalmologist, using the image on the left in which the contrast of the objects (letters of the alphabet) varies with each line. The relative visual contrast sensitivity for a patient is determined by the lowest line (object contrast) they can read.

For X-ray imaging, specifically mammography, the test object, or phantom, illustrated on the right is used by physicists. It contains several groups of objects to evaluate different image characteristics. For contrast sensitivity it is a series of round objects that have varying thicknesses providing different physical contrast. The relative contrast sensitivity is determined by the number of objects visible in an image.

The visibility of low-contrast objects in medical imaging is also affected by *visual noise* that will be considered later. The test described above can also show the effects of noise on visibility.

The contrast sensitivity for a specific imaging procedure is determined by a combination of factors including the design and technical capabilities of the imaging equipment and the control and adjustment of the variable technical factors for each patient imaging procedure.

Over the years, *visibility* of the interior of the human body has dramatically expanded with discoveries, inventions, and developments of technology and imaging methods that increased contrast sensitivity. Here we consider the general concept and then the details.

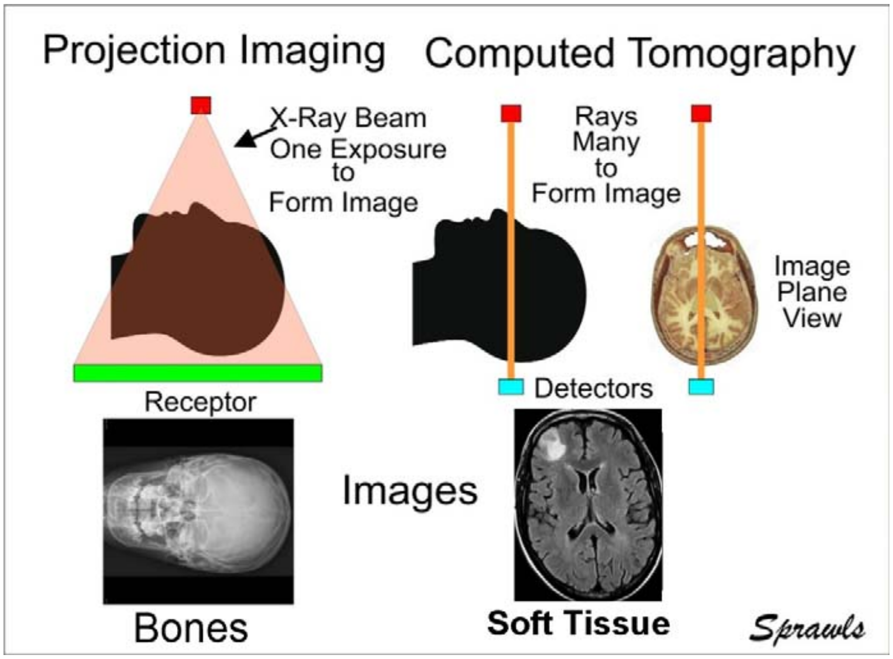


Contrast sensitivity is a characteristic of an imaging procedure that is controlled by a combination of other factors, some the design of the equipment, others were the adjustable factors by the operator setting up the “technique” or “protocol” for the procedure. The general concept is illustrated here. The visibility is extended to the objects with lower physical contrast with increased contrast sensitivity of the imaging procedure.

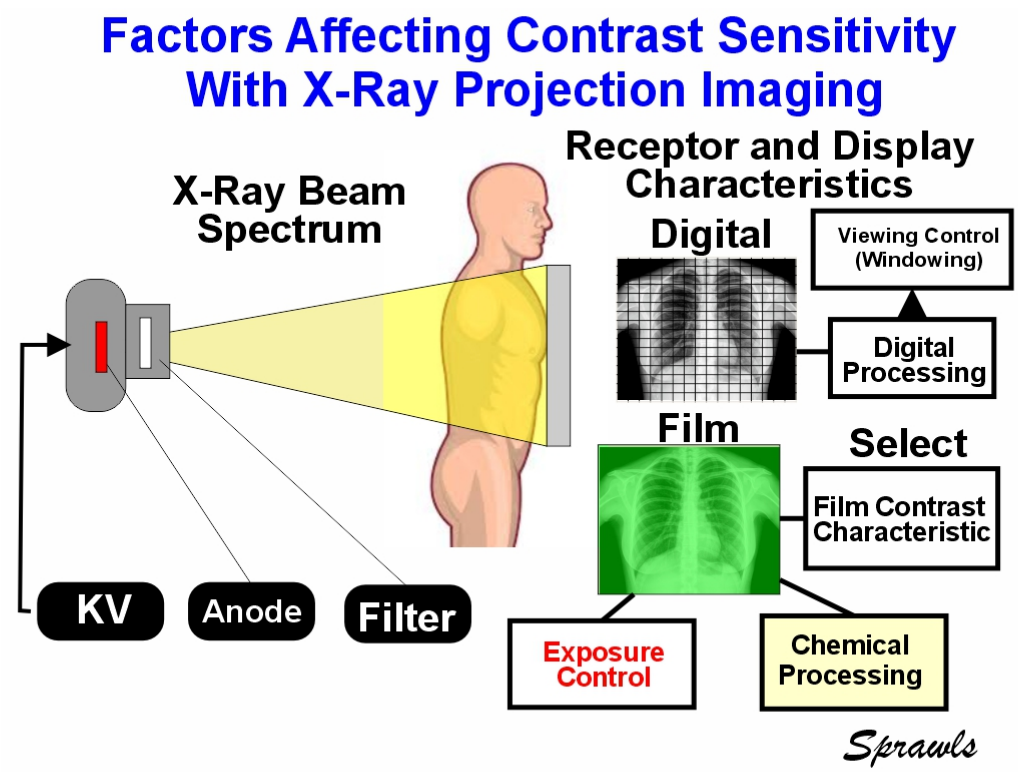
The contrast sensitivity with X-ray imaging depends on the characteristics of the imaging procedures with a major difference between the two viewing methods, projection imaging and computed tomography as illustrated here.

Projection imaging, first introduced and demonstrated by Roentgen, continues to be the fundamental principle of both radiograph and fluoroscopy as practiced today. Although many advances have been made, as described later, contrast sensitivity has generally been limited to imaging high-contrast bones, the chest, and contrast media, with one exception, mammography, as described later.

The invention and development of computed tomography (CT) revolutionized medical imaging by extending contrast sensitivity to include the soft tissues, especially those within the skull.



Contrast Sensitivity with Projection X-ray Imaging



A continuing effort beginning with Roentgen's introduction of X-ray imaging of the interior of the human body has been to expand the scope of *visibility* to include more objects and conditions, especially those that are of clinical significance, for example the early detection of cancer. This has occurred with inventions, discoveries, and developments addressing each of the image and imaging procedure characteristics that affect visibility. By far, the most significant is the *contrast sensitivity* of the imaging process. This is determined by a complex combination of many factors as illustrated here. These are in two categories, those associated with the X-ay beam and those associated with the receptor and display of an image.

The X-ray Beam Spectrum and Contrast Sensitivity

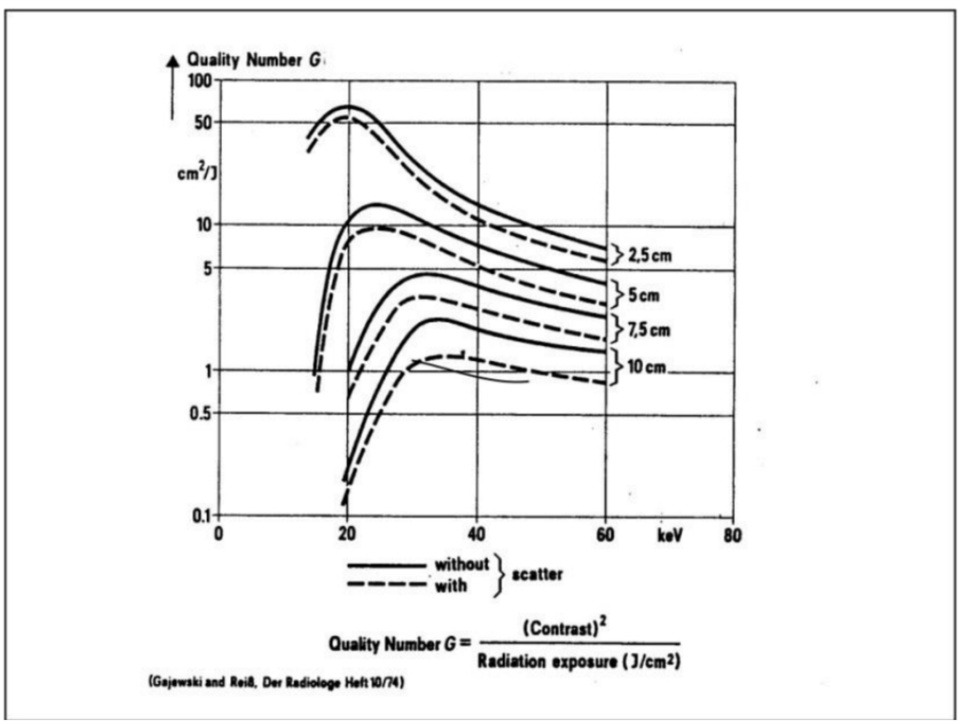
The physical contrast that is visualized with all forms of X-ray imaging is the difference in X-ray attenuation between the various tissues or other materials in the body, As observed previously, this depends on physical density and atomic number (Z). The effect of Z on visible contrast is heavily dependent on the X-ray spectrum, being most effective with the spectrum photon energies just above the K-edge energy of the tissue components where the photoelectric effect is most prominent. However, with higher photon energies where the Compton interaction is prominent, density differences between tissues is source of contrast.

For the relatively low atomic numbers (Z) of the components of the human body the x-ray attenuation decreases with increased photon energy within the x-ray spectrum. This produces two generally conflicting effects. The difference in attenuation, the source of physical contrast, decreases. However, the attenuation by the human body decreases which reduces the exposure or radiation dose to the patient required to deliver the necessary exposure to the receptor that will produce an appropriate image.

This has been the challenge throughout the history of x-ray imaging, providing an X-ray beam with a spectrum that balances the requirements for contrast sensitivity (visibility) and lower exposure to the patient. This is an optimized spectrum. For general x-ray imaging, both radiography and fluoroscopy, over the years tubes with tungsten anodes and added aluminum filtration were used. The KV was the adjustable factor that could be used for each patient procedure to optimize visibility with exposure to the patient.

Generally higher KV values (100 – 120kV) and sometimes additional filtration were used for imaging the chest because of the high physical contrast, density differences, within the chest. A KV value of around 70kV produced a spectrum with a peak or maximum intensity close to the K-edge energies of the contrast media, iodine, and barium. This would produce maximum contrast but sometimes not adequate penetration through the thicker body sections and higher KV values are used. For the thin extremities, especially hands, lower KV values are used than in addition to showing the bones provides some visibility of the soft tissues that can be of diagnostic value.

The breast which is composed only of soft tissues remained a challenge, and a method for visualizing the breast tissues was desperately needed to detect cancer, especially in the early stages when treatment can be most effective. This would require an X-ray beam spectrum with much lower energy than could be produced with the conventional radiographic systems. The specific challenge was to produce a spectrum that was optimized to balance the requirements for contrast and visibility along with minimizing radiation exposure to the patient. A major development was the research by Gajewski & Reiss and the publication of the results shown here.



They conducted experiments with phantoms simulating breasts of different thicknesses measuring contrast of an embedded object and the exposure to the simulated breast. A quality number (G) was defined as the ratio of the square of the contrast to the radiation exposure. When the quality number is plotted in relation to X-ray photon energy as shown above two major facts are revealed.

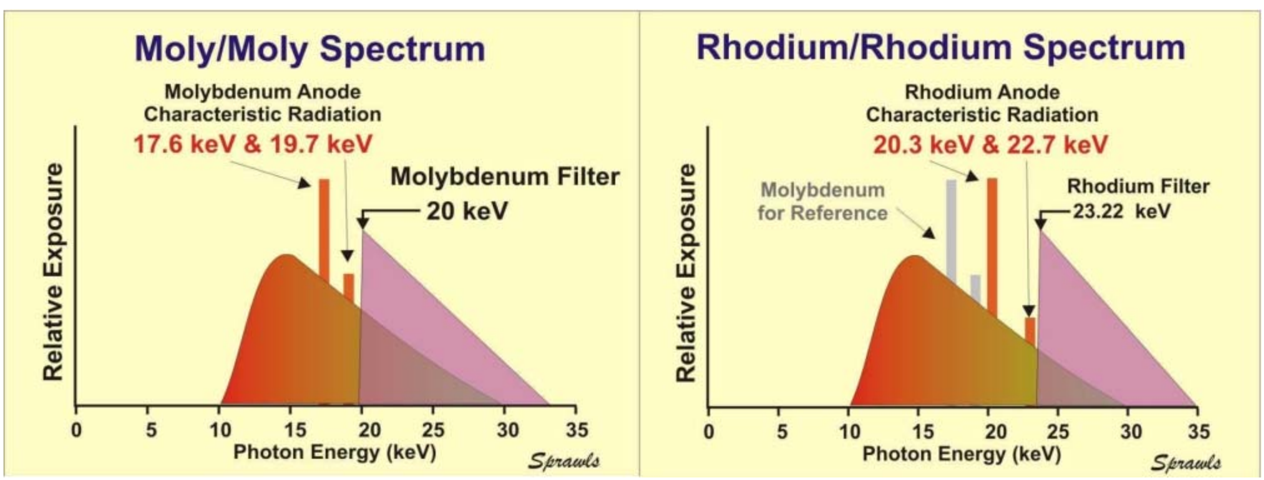
- For each specific breast thickness there is a photon energy that produces the maximum contrast (visibility) in relation to radiation exposure.
- With increasing breast thickness, the peak in quality number moves to a higher photon energy and the quality number representing the ratio of visibility to radiation exposure decreases.

This was to give direction for developing the technology that would produce optimized spectra to be the foundation of X-ray mammography for years to come. This, along with many other innovations is described in:

THE SCIENTIFIC AND TECHNOLOGICAL DEVELOPMENTS IN MAMMOGRAPHY A CONTINUING QUEST FOR VISIBILITY
P. Sprawls. MEDICAL PHYSICS INTERNATIONAL Journal, vol.7, No.3, 2019
http://www.mpijournal.org/pdf/2019-SI-02/MPI-2019-SI-02-p141.pdf

The first was to modify existing X-ray tubes having tungsten anodes by replacing the glass windows and aluminum filters with lower atomic number beryllium so that the low energy photons would not be attenuated. The generators (electric power supplies) were modified to provide KV values in the 30 kV range…well below what is used in conventional radiography. The spectra produced with this technology provided the foundation for establishing mammography as a highly valuable imaging method for detecting and diagnosis cancer.

The bremsstrahlung spectrum produced with a tungsten anode, minimal filtration, and low KV produced good contrast but was somewhat broad and spread beyond the optimum energy to maximize contrast and visibility in relation to radiation exposure to a patient. The next major innovation was the development of X-ray tubes with anodes to produce characteristic radiation at the desired energy and filters with K-edge energies to attenuate the higher energy bremsstrahlung. The first was molybdenum for both anode and filter and later tubes with dual anode tracks to include rhodium and a rhodium filter. This provides several combinations of anodes and filters to produce spectra as shown here.



After considering the compressed thickness and density of a patient's breast the technologist could select from the available anode and filter combinations and a KV value, generally in the range of 26kV-40kV, that would produce an optimized X-ray beam spectrum for extending visibility to more of the human body and signs of a major and deadly disease, cancer. With the development of low photon energy spectra as applied in mammography visibility was extended to the differences, or contrast, among the soft tissues in the body.

The challenge of the Brain

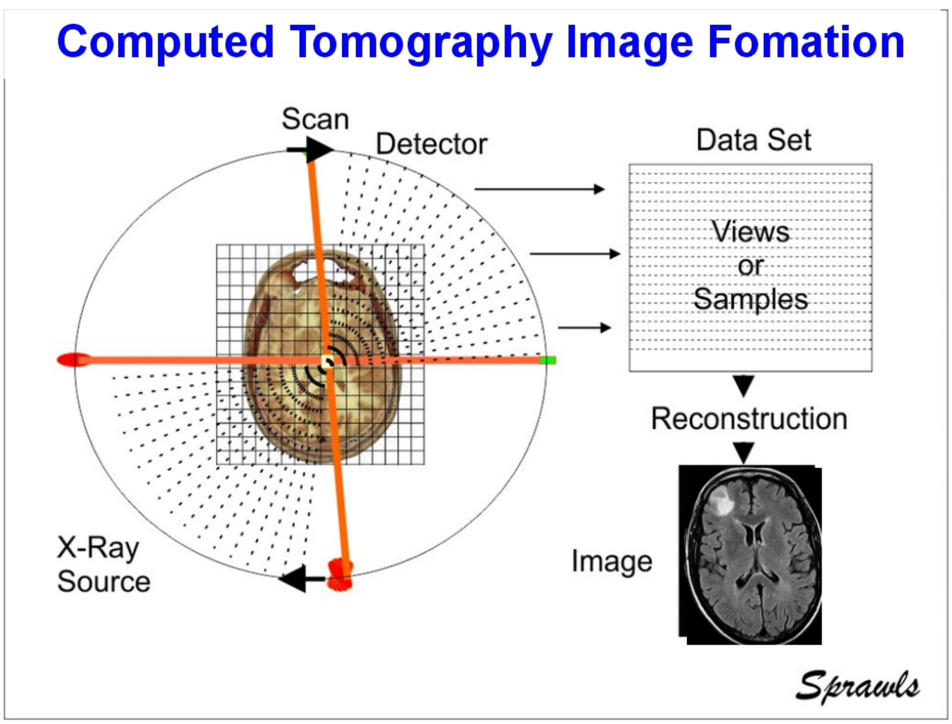
One organ, the brain, remained a challenge because it is enclosed in the dense skull. The low photon energy spectra that can produce contrast among the soft tissues cannot penetrate the head. Radiography of the head was a valuable procedure for visualizing the skull, especially to diagnose malformations and fractures, but the soft tissues of the brain remain invisible.

What was needed was an imaging method with an X-ray beam that could penetrate the skull and visualize the physical contrast (density) of the brain's soft tissues. This was not possible with conventional radiography using an X-ray beam projected through the body and forming "shadow" images.

Godfrey Hounsfield was an engineer on the staff of EMI in England and worked on many projects during his career. Although it was not one of his major projects he had an interest in computerized imaging, pattern recognition, etc. The legend is he was on vacation along with a physician and they were having discussions about imaging, assumed from their different perspectives. The physician explained that a major problem was being able to image the brain because it was enclosed in the dense skull. This motivated Hounsfield to develop a solution. That was to extend his research and to develop the new technology, computed tomography (CT). The details of this development and continuing evolution over the years is presented here:

THE MANY STEPS AND EVOLUTION IN THE DEVELOPMENT OF COMPUTED TOMOGRAPHY TECHNOLOGY AND IMAGING METHODS, THE QUEST FOR ENHANCED VISIBILITY The First Fifty Years
P. Sprawls. MEDICAL PHYSICS INTERNATIONAL Journal, vol.7, No.3, 2019
http://www.mpijournal.org/pdf/2020-SI-04/MPI-2020-SI-04-p351.pdf

The specific contribution of computed tomography (CT) was to provide adequate contrast sensitivity for visualizing the soft tissues of the brain within the dense skull. The details are described in the publication referenced above but are illustrated and summarized here.



Computed tomography, which provided high contrast sensitivity, especially for imaging the brain, also introduced a revolutionary approach to medical imaging that was to be followed by future imaging modalities, MRI, and SPECT. That was a method producing images of slices of the body (tomograms) that had consisted of two distinct phases. Image formation is in two phases. The first phase, generally referred to as *scanning* passes a narrow x-ray beam through the body from many directions that measures the total attenuation along each path. The second phase, designated as *image reconstruction*, uses a mathematical transform (the actual foundation of computed tomography) that transforms the attenuation values for each path through the body into attenuation values for individual voxels in a matrix forming a *digital image*.

The high contrast sensitivity is possible because the attenuation values (coefficients) for the individual voxels (to be displayed as image pixels) are sufficiently different that can be displayed in an image with different brightnesses, or *visual contrast* using the processing illustrated here as published by Hounsfield.

Vol. 46, No. 552

G. N. Hounsfield

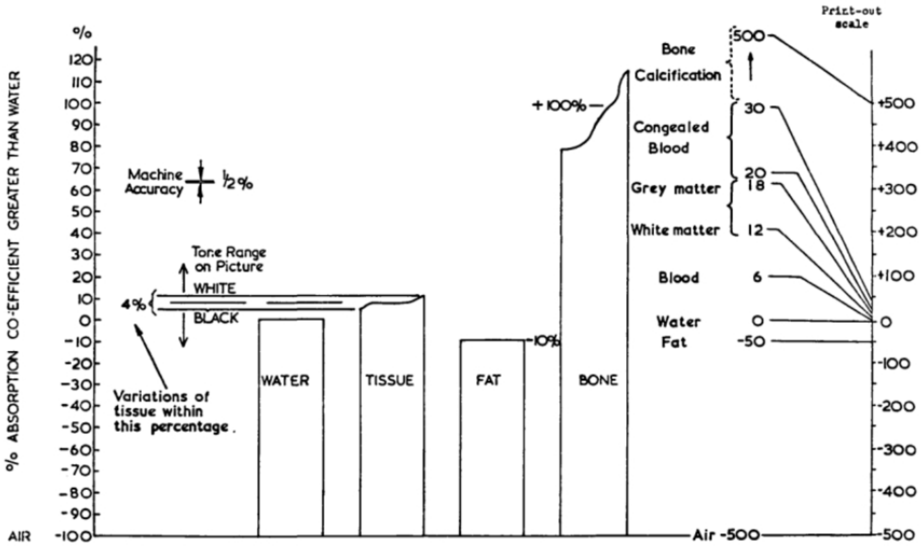
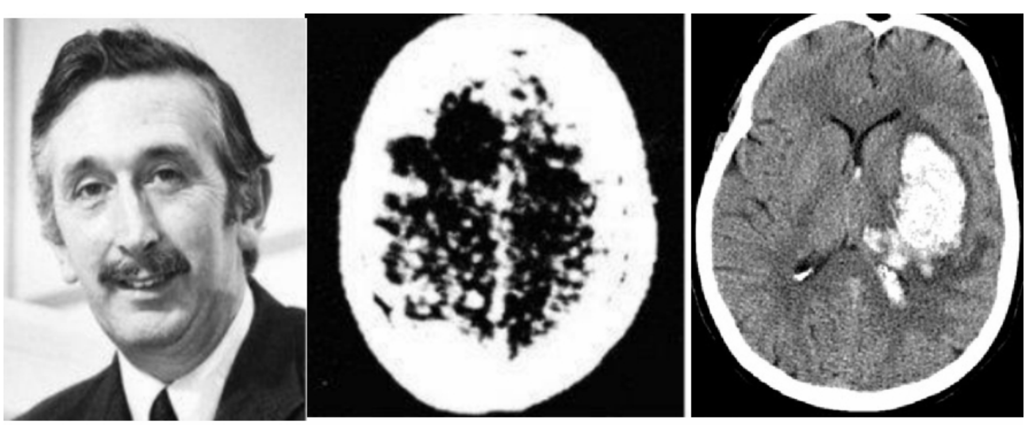


Fig. 9.

Illustration of machine sensitivity. The scale on the right is an arbitrary scale used on the print-out and is related to water = 0, air = 500 units. It can be seen that most materials to be detected fall within 20 units above zero and can be covered by the adjustable 4 per cent "window".

Hounsfield developed a scale of relative attenuation values in relationship to water with a value of zero. Tissues that were denser than water had positive values and those less dense, fat for example, had negative values. The scale extended from -500 for air to +500 for bone. This was later to be designated as the Hounsfield scale and numbers.

The significance was the numbers for the tissues were sufficiently different to provide visible contrast when printed out or displayed in an image. This was achieved using a "window" when viewing that selected a small range of numbers (for example, representing the soft tissues) and displayed over a wide range of brightness levels (from black to white) in the viewed image.



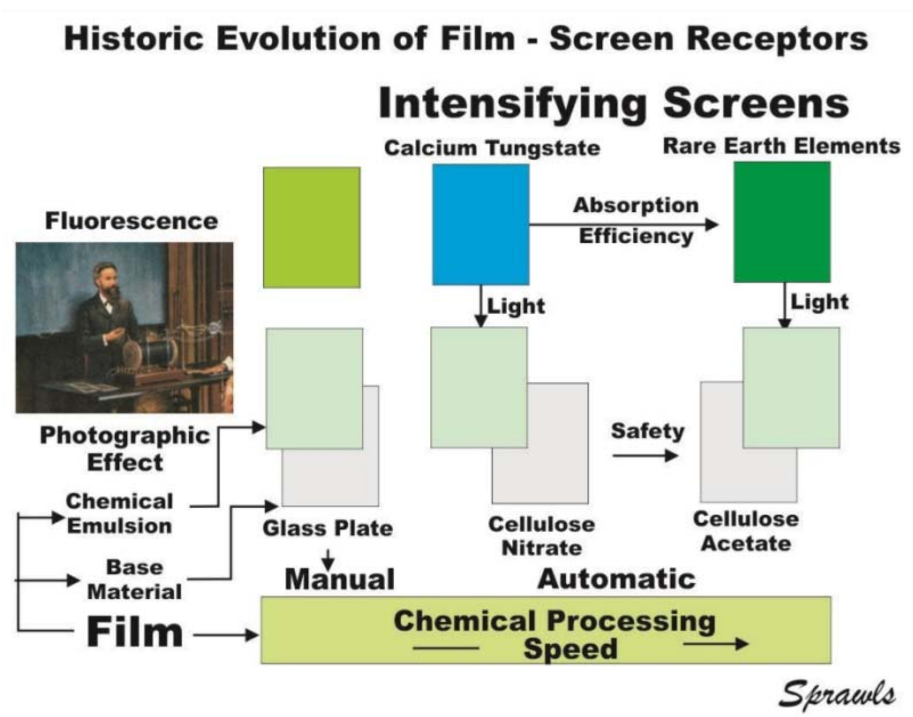
Hounsfield | **Early Image 1971** | **50 Years Later**

The historical significance of one the early CT images shown here stands along with the X-ray image of a human hand demonstrated and presented by Roentgen in 1896. Visibility into the human body had now been extended to include the brain enclosed within the skull. The significant factor was that the signs of a disease, a tumor, were visible. The general quality was very inferior compared to future images, but it did demonstrate a contrast sensitivity providing visualization of brain tissues and a disease for the first time in history. This was to be followed by many developments in the CT technology and methods addressing other image characteristics to expand visibility to include many conditions within the brain and to become a major diagnostic method in the field of neurology and the expanding specialization of neuroradiology.

Image Receptor Characteristics and Contrast Sensitivity.
As indicated in a previous illustration there are several characteristics of the receptors in X-ray imaging that influence contrast sensitivity and visibility. For around a century following Roentgen's introduction photographic type film was the component of the receptor for recording and displaying an image. The film could be exposed directly by the X-ray beam or most often, by light from a fluorescent intensifying screen that was in contact with the film. Because film is much more sensitive to light than X-radiation images could be made with much less radiation to a patient by using intensifying screens.

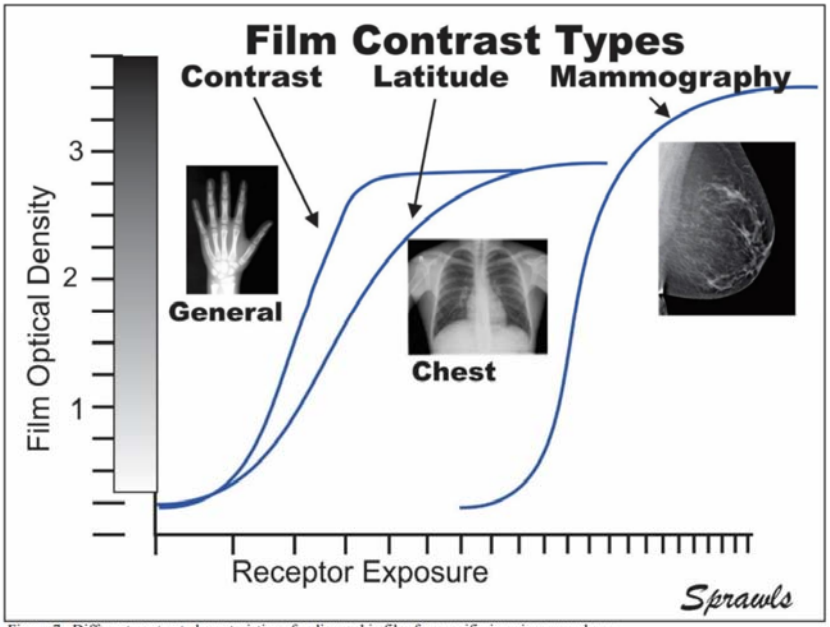
Characteristics of both the film and the intensifying screens had significant effects on visibility but it was characteristics of the film that affected contrast sensitivity. During the first century both film and intensifying screens benefited from a series of innovations and developments to increase visibility and minimize the radiation exposure to the patient and is described here.

FILM-SCREEN RADIOGRAPHY RECEPTOR DEVELOPMENT A HISTORICAL PERSPECTIVE
P. Sprawls. MEDICAL PHYSICS INTERNATIONAL Journal, vol.7, No.3, 2019
http://www.mpijournal.org/pdf/2018-SI-01/MPI-2018-SI-01-p56.pdf

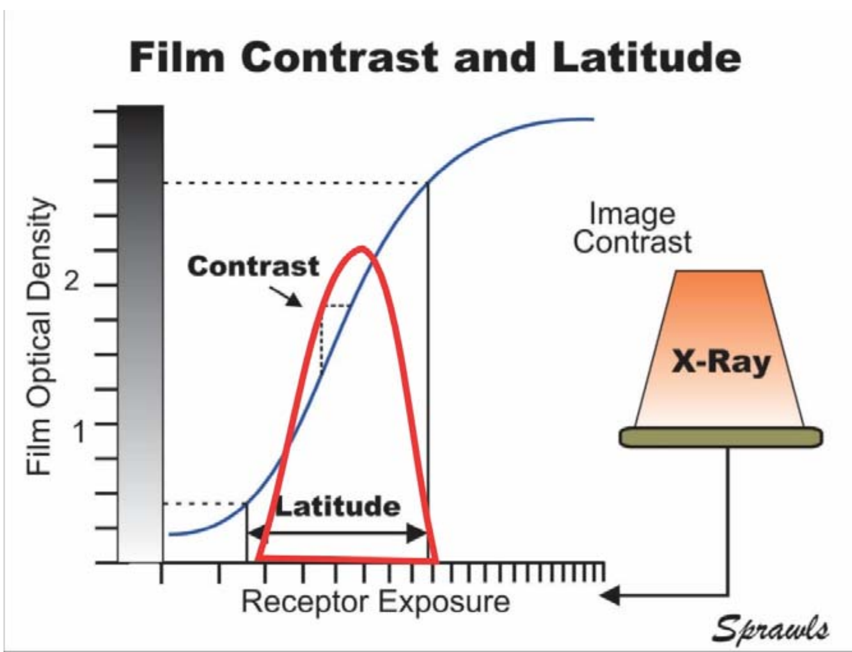


A major effort during his time was to develop film with contrast characteristics that would provide the best visibility for the different anatomical regions, the chest being very different from the breast.

The contrast characteristic of a film can be described with the contrast, or H & D graphs as shown here.



These curves show the relationship between film density (visible brightness) and exposure to the film. It is the slope of the curve at every point that represents contrast.



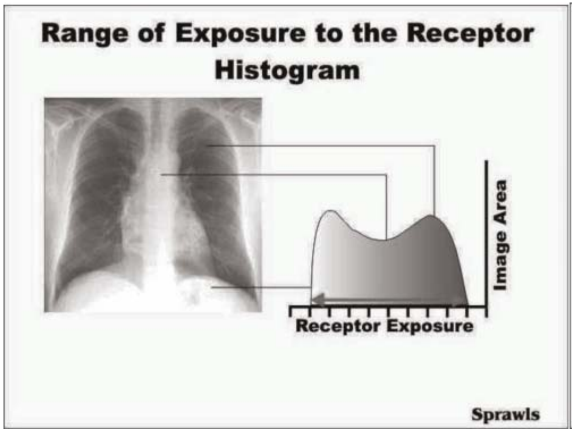
As illustrated here, there is a limited range of exposure that is within the slope of the characteristic curve that will produce image contrast. This is within the latitude of the film.

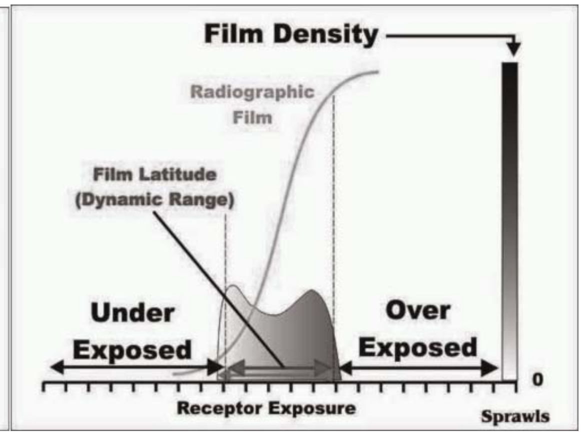
Selecting the appropriate film for a specific procedure was the first step but the next two were the critical ones for obtaining maximum contrast and visibility.

Maximum contrast requires the exposure reaching the receptor to be within the latitude range of the film…not always easy to do. The exposure factors (KV, MAS) for the procedure must be adjusted in relation to the size and anatomical location of the patient. If an automatic exposure control (AEC) is used it must be properly calibrated, adjusted, and positioned. Variations in the chemical processing can both reduce the contrast and shift the latitude range contributing to errors in exposure.

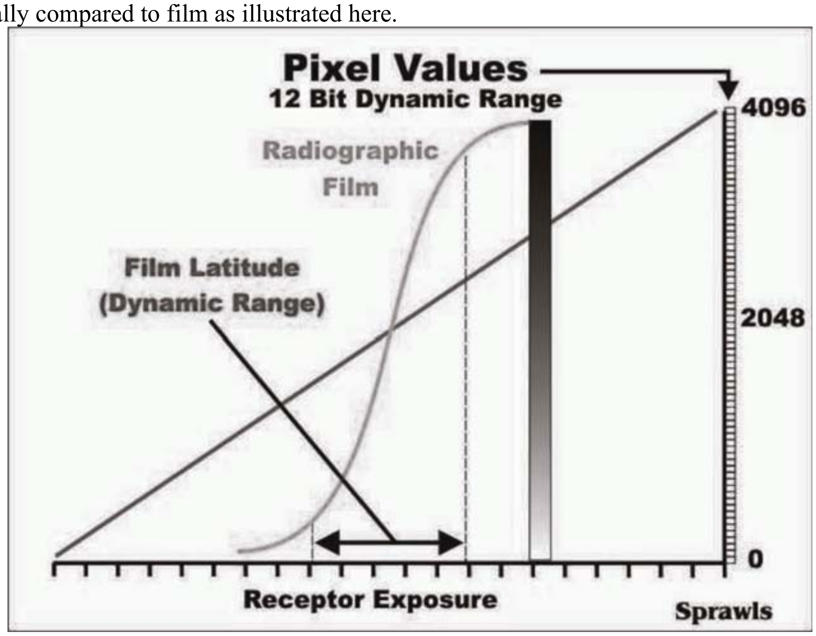
While film was a valuable receptor and display medium for many years its limitations for providing maximum contrast and visibility as described here and along with many other factors including cost, difficulties with the chemical processing, storage and retrieval, and limited control with viewing, were reasons for it to be replace with digital imaging as that technology was developed.

Digital radiography provides many advantages over film but our interest here is specifically in its contribution to increasing visibility throughout the body. As illustrated above with film radiography, the X-ray exposure penetrating the patient's body must fit within a relatively narrow range to produce maximum contrast and visibility. That is within the latitude of the film. This was often a challenge because of errors in adjusting the exposure and the range of exposure from the body. That can be expressed as a histogram and compared to the range of film exposure that can produce adequate contrast as illustrated here.

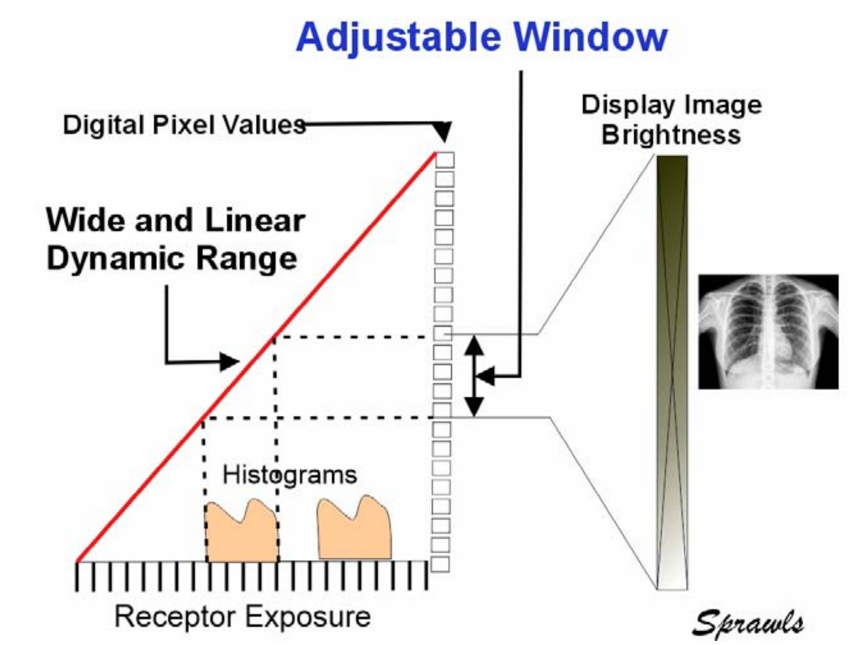




Digital radiography uses several different technologies for the receptor, but a common characteristic is they have a wide *dynamic range*, especially compared to film as illustrated here.



A digital image is recorded as a matrix of pixels with each pixel having a numerical value that has a long and linear relationship to the X-ray exposure to the pixel area. This is very different from images recorded on film that has a short and curved relationship between exposure and displayed film optical density or brightness.



With respect to contrast and visibility the great contribution of digital imaging was the ability to record the image data with a wide dynamic range so that no data was lost, as was possible with film, and then select the range of the recorded data, the histogram, and display it over the full brightness range using the window control.

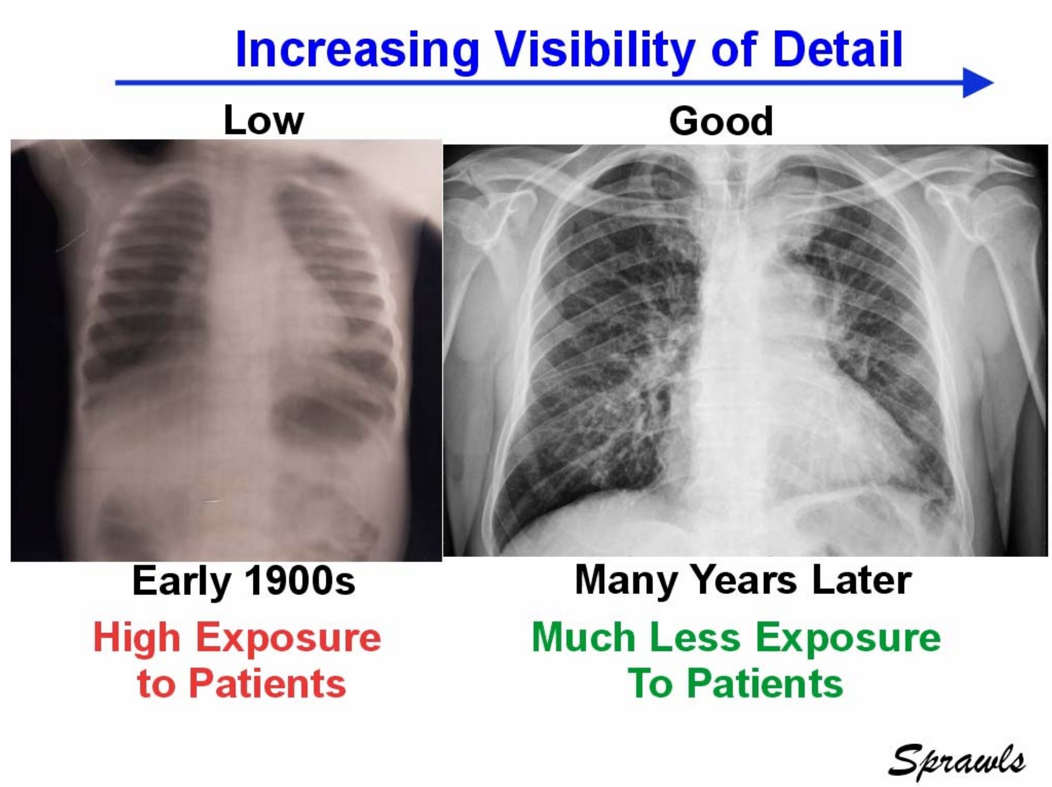
This capability was not only used in digital radiography, but also the other modalities that produced digital images, CT, MRI, and SPECT. It was a major development extending the range of contrast sensitivity throughout the human body.

Contrast Sensitivity in Summary

The fundamental requirement for X-ray imaging is the ability to "see" or visualize structures and conditions within the human body. These vary in several characteristics including their *physical contrast.* Only the large bones were visible in Roentgen's first images because they were dense, thick, and composed of calcium. A series of investigations and developments addressed the X-ray beam spectrum and optimizing it for visibility in different anatomical regions, ranging from the high-contrast chest to the challenging breast with very low physical contrast between the soft tissues. Receptors with film were used for almost a century. Even with some improvements in contrast characteristics over the years the challenges of limited latitude (dynamic range), obtaining correct exposure, and requiring chemical processing with its cost and variability established it for replacement with digital when that technology was developed. Digital imaging provides a wide and linear dynamic range with the ability to window and enhance contrast for selected tissues and anatomical regions. This was the function that enabled CT to provide very high contrast sensitivity and expand visibility in the body, especially to the brain.

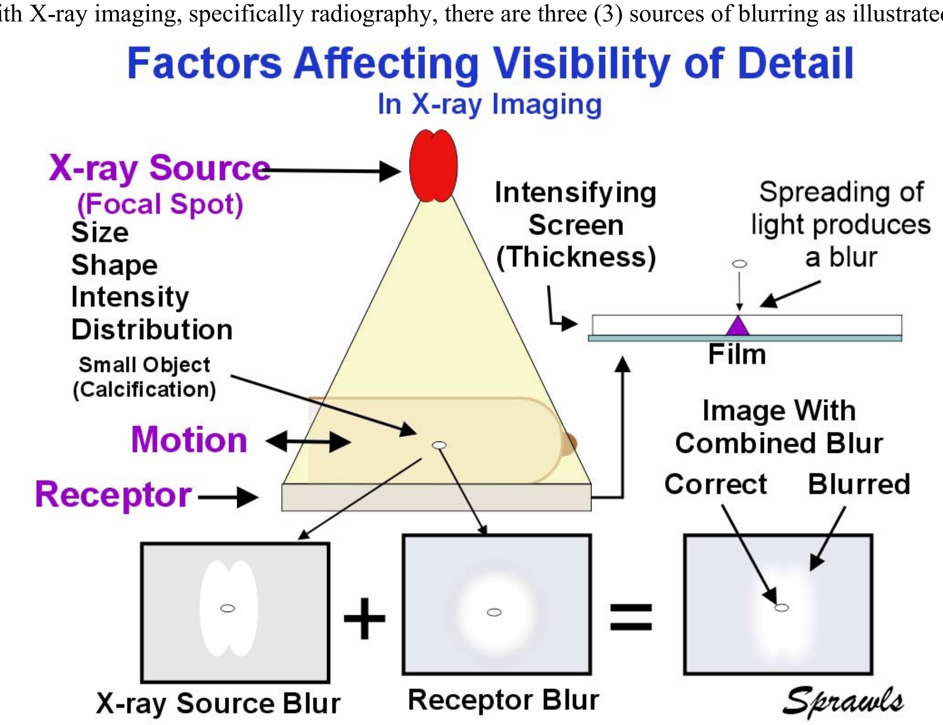
VI. VISIBILITY OF DETAIL

Following the introduction of X-ray imaging by Roentgen it was the visibility of the physical contrast between the different tissues and other materials in the body that revolutionized the practice of medicine. As we have just read and seen, this was followed by many years of research and development to extend visibility to include items with low physical contrast, especially female breast, and the brain within the skull. There were many items of clinical significance that remained invisible because of their size, they were too small to see and generally designated as *anatomical detail***.** Along with efforts to increase contrast sensitivity over the years there was also attention to increasing *visibility of detail* as illustrated here.



As new technologies and methods were developed a major consideration was reducing the radiation exposure to patients and optimizing it with the requirements for visibility.

With all imaging methods, including human vision, it is the blurring within the process that limits visibility of detail, the small things. With X-ray imaging, specifically radiography, there are three (3) sources of blurring as illustrated here,



For more than a Century many inventions and developments have contributed to increased visibility of detail in X-ray images. These have concentrated on the three (3) sources of blurring: the x-ray source, the design of the receptor, and motion of the patient during the exposure to form the image.

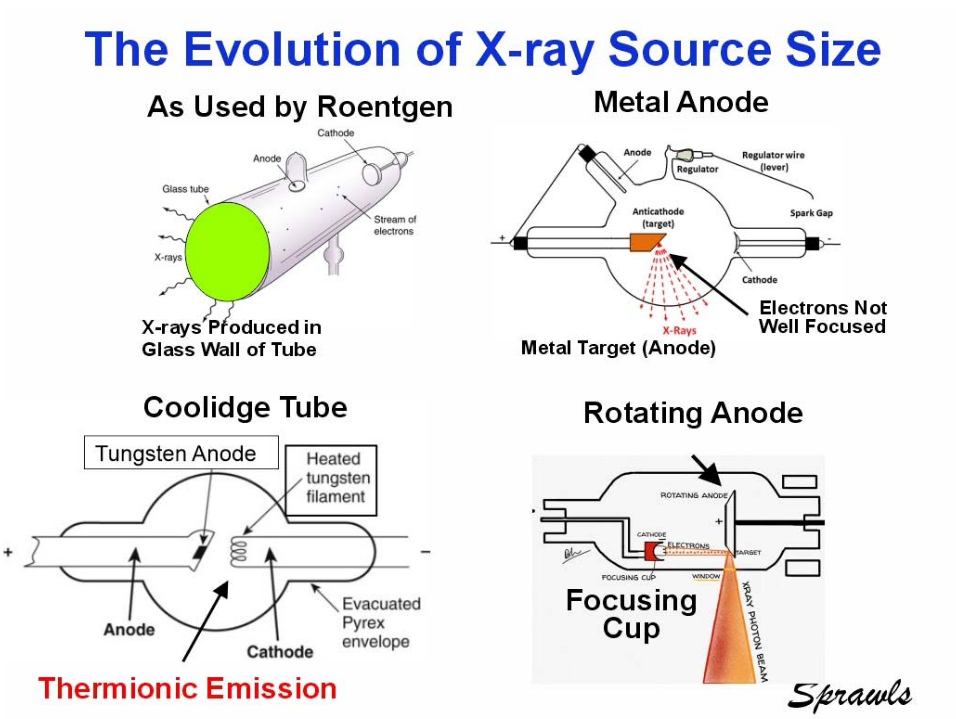
Blurring by the X-ray Source

When images are formed by projecting an X-ray beam through the human body the "sharpness" of the shadow image is affected by the size of the X-ray source in combination with the geometry of the procedure, that is the distances between the source, patient. and receptor. It is the blurring, sometimes perceived and described as "un-sharpness" that reduces the visibility of small objects, that is visibility of detail. For a specific geometry the blurring and visibility of detail is determined by the characteristics of the X-ray source: size, shape, and the distribution of radiation intensity over the area of the source.

A continuing effort following the introduction of X-ray imaging by Roentgen has been to reduce the size of the radiation source, that were to become known as *focal spots.* That along with the story of many other innovations in X-ray tubes is provided here.

X-RAY TUBES DEVELOPMENT - IOMP HISTORY OF MEDICAL PHYSICS
Rolf Behling, Philips Healthcare Roentgenstrasse 24, 22335 Hamburg, German
MEDICAL PHYSICS INTERNATIONAL Journal, Special Issue, History of Medical Physics 1, 2018 8
http://www.mpijournal.org/pdf/2018-SI-01/MPI-2018-SI-01-p08.pdf

Four phases of that development related to source or focal spot size are shown here.



Roentgen's Tube

The tube used by Roentgen at the time of the discovery and early experiments was not designed to be an X-ray tube, but for other demonstrations and experiments. When energized with a high voltage, electrons from the ionized low-pressure gas were accelerated toward the end of the tube and striking the glass wall that became the radiation source. It was large in area but not an efficient X-ray source.

Metal Anodes

Roentgen quickly discovered that metal was much better than glass for producing X-radiation and had tubes prepared with several types of metal anodes as the source. For at least the next 20 years tubes with metal anodes were manufactured and used around the world to establish X-ray imaging as a valuable medical procedure. These tubes contained a low-pressure gas that was ionized to produce the electrons that struck the anode to produce the radiation. They were not well focused, and the size of the source was large, compared to later tubes. The quantity of electrons from the ionized gas was very limited and the low X-ray production required long exposure times to image a patient.

The Cooledge Tube

William Coolidge was a scientist and engineer who in 1905 joined the General Electric Research Laboratories with his first work to improve lightbulb filaments. His research resulted in the development of so-called "ductile tungsten" that was to become the filaments for lightbulbs for many years.

He recognized tungsten had several properties that made it valuable for use in X-ray tubes. Both as an anode and a cathode that could be heated to a very high temperature where it would emit electrons, thermionic emission. This made the cathode the actual source of electrons rather than the ionized gas in the tube. The advantage was dramatically- higher tube currents (MA) and X-ray production. The tube current (MA) could be regulated by adjusting the temperature of the cathode filament. The other major advantage was with the addition of a focusing cup to the cathode the electron beam could be focused to produce small focal spots as the X-ray source.

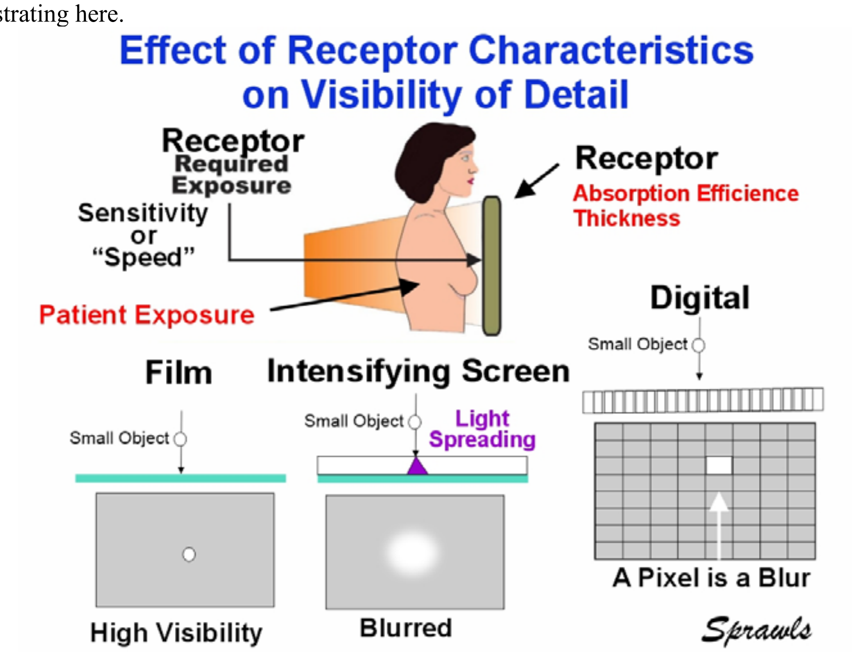
Rotating Anodes

The availability of small focal spots, in the order of a millimeter, was a major advantage extending visibility of detail but created another problem. Most of the energy of the electrons bombarding the anode is converted to heat. When this heat is concentrated in small areas on the anode, melting and damage can occur. The introduction of rotating anodes provided for spreading the heat over a large area and permitted tubes to be operated with much higher currents and X-ray output. The design of tubes with smaller anode angles permitted even smaller effective (projected) focal spot sizes in relation to the actual area where the heat is produced.

Effects of Receptors on Visibility of Detail

The design of the receptor that "receives" the X-ray beam after it has passed through the patient's body and transforms it into a visible image has a significant effect on the *visibility* of detail. This is because of the blurring introduced into the image.

The ongoing research and development of receptors for X-ray imaging, specifically radiography, includes three (3) major types, or phases illustrating here.



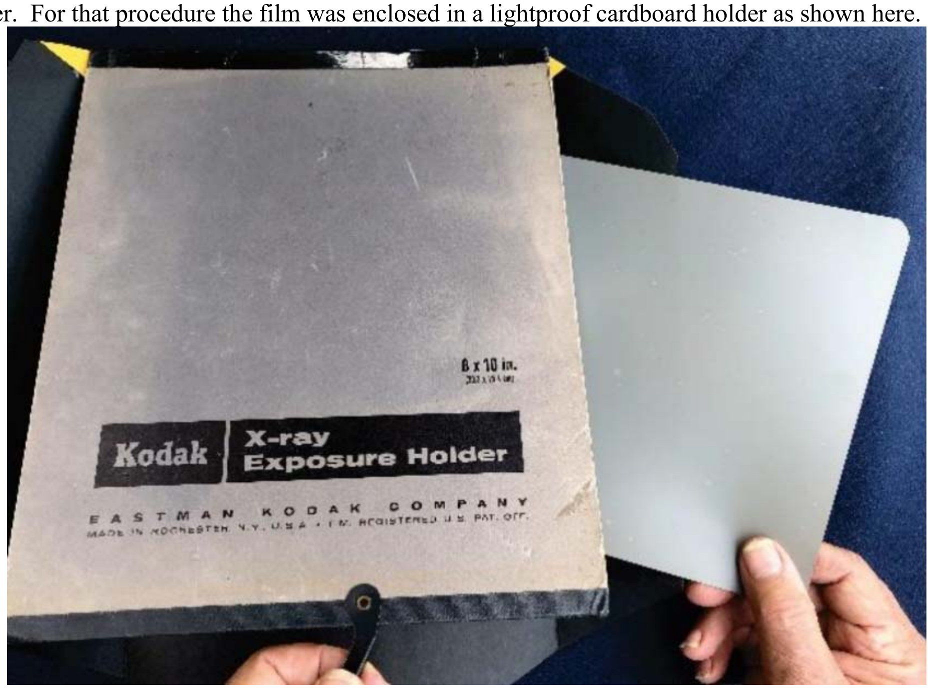
First introduced by Roentgen was photographic type film that he had discovered was sensitive to X-radiation and could be used to record images. The next and long-lasting phase was using fluorescent intensifying screens to first absorb the X-radiation and use the light to expose the film. The final and continuing phase is using digital technology. Each of these technologies have design characteristics that affect and generally limit visibility of detail.

A highly significant and related factor is the quantity of radiation required to form an image and that also affects the radiation delivered to the patient. The selection of a receptor for a specific patient procedure often requires a decision on balancing the need for visibility of detail while minimizing the exposure to the patient.

The first function of a receptor is to *absorb* the X-radiation and then convert it into a visible image, often requiring several steps. The absorption by a specific receptor is determined by absorption efficiency of the material and the thickness of the receptor. It is the thickness of the absorbing receptor material that is critical to visibility of detail because blurring can occur within that thickness,

Film as a Receptor

Photographic type film was the first receptor discovered and used by Roentgen, and it was generally available. The X-radiation was absorbed in the very thin emulsion layer and produced excellent visibility of detail. However, the thin emulsion layer was not an effective radiation absorber and required very high exposures to produce an image. With no alternative at that time, film continued to be developed and used as the receptor. This included the emulsion coated on large glass plates and used for large anatomical regions, especially the chest. Even after intensifying screens were developed and became the standard for general radiography, Film directly exposed by the X-radiation continued to be used for procedures requiring high visibility of detail, especially mammography for visualizing very small calcifications, a significant sign of early breast cancer. For that procedure the film was enclosed in a lightproof cardboard holder as shown here.

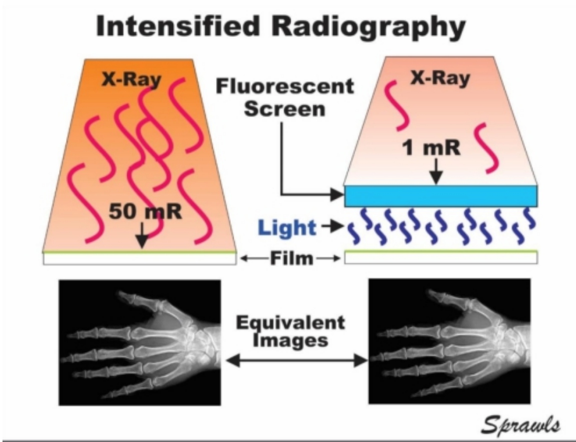


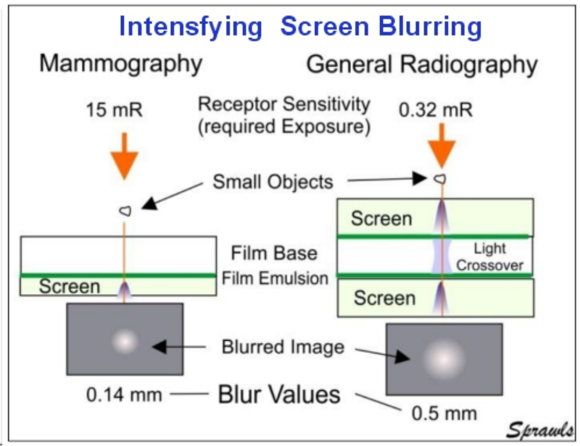
Excellent visibility of detail, the calcifications, but with a concerning high exposure to the patient.

Intensifying Screens and Reduced Exposure

One of Roentgen's first discoveries was that the *New Kind of Radiation* interacted with fluorescent materials and produced visible light. This is how he viewed the first image, and fluorescent screens quickly became the receptors for fluoroscopy procedures and for many years to come.

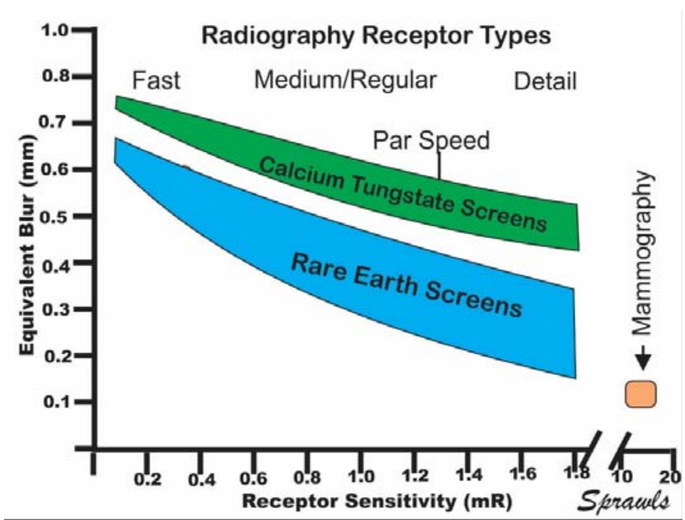
Thomas Edison, a prolific inventor, discovered that Calcium Tungstate was a fluorescent material apparently interested in it a source of light. However, it was not until around the 1910s that many of the technical issues were resolved and practical intensifying screens for clinical imaging became available. The advantages and disadvantages of intensifying screen for X-ray imaging are illustrated here.





When a fluorescent screen is placed in contact with a film it creates an X-ray image receptor that requires much less X-ray exposure to form an image compared to exposing the film directly. This is because the thicker layer of material, like Calcium Tungstate, is a much more efficient X-ray absorber than the thin silver halide emulsion layer of the film. This is sometimes expressed as the intensification factor and an example value of 50 is shown. While the use of intensifying screens provides a dramatic reduction in exposure to patients, the trade-off is a reduction in visibility of detail caused by the spreading of the fluorescent light within the thickness of the intensifying screen as illustrated on the right. The amount of blurring depends on several factors, the most significant being the thickness of the screens. That is the problem, thicker screens are needed for increased X-ray absorption and reduced exposure, but thicker screens produce more blurring. Generally, when intensifying screens were used in a clinical facility there was diffident types to select from depending on the need for visibility of detail. The two major types are illustrated. For mammography that requires high visibility of detail to visualize very small calcifications a single thin intensifying screen is used, for general radiography, two screens to increase X-ray absorption were placed on both sides of film with emulsion on each side as illustrate.

Around the 1970s several so-called “rare-earth” fluorescent materials became available and began to replace Calcium Tungstate in a next generation of intensifying screens, The advantage was a higher X-ray absorption because their atomic number (Z) values positioned their K-edges near the peak intensity of the typical X-ray beam spectrum. The general choices that existed are shown here.

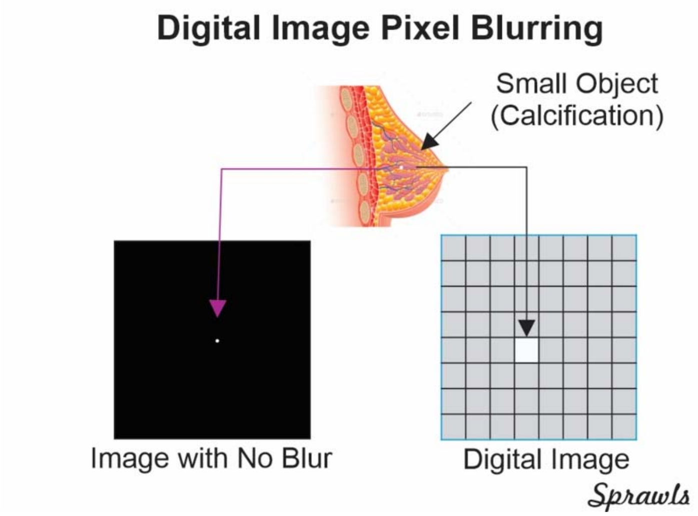


Generally, there were four (4) types of receptors that could be selected from, three (3) for general radiography and mammography that were very different from the others because of the need for high visibility of detail. The physical difference among the types was the thickness of the intensifying screens. The Medium/Regular type was used for many procedures, Detail used for imaging the bones in the extremities, and the Fast to minimize exposure and perhaps for large patients that were difficult to penetrate with the X-ray beam.

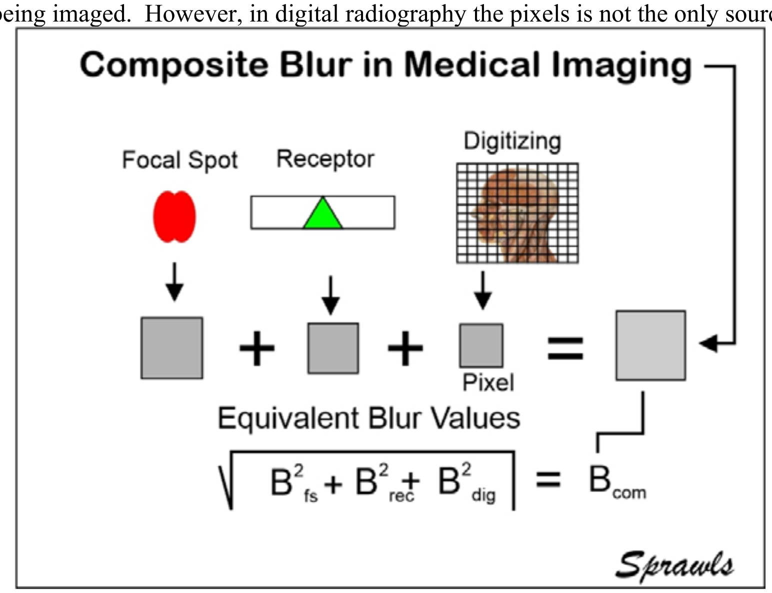
More details on the developments and evolution of intensifying screens is in the previously cited reference and can be viewed here: http://www.mpijournal.org/pdf/2018-SI-01/MPI-2018-SI-01-p56.pdf .

And Then There Was Digital

As computers and digital technology, especially for imaging, continued to develop it offered many advantages over film-based radiography. However, there was one concern. Digitizing an image could potentially reduce *visibility of detail*. Here our interest is only on the blurring effect of digitizing an image, not other details of the digitizing process,



In a digital image the individual pixels are the smallest thing displayed. For a small object, like the calcification shown here, it will be displayed as a pixel. In effect, a *pixel is a blur*. To maintain visibility of detail an image pixel needs to be smaller than the objects being imaged. However, in digital radiography the pixels is not the only source of blurring.

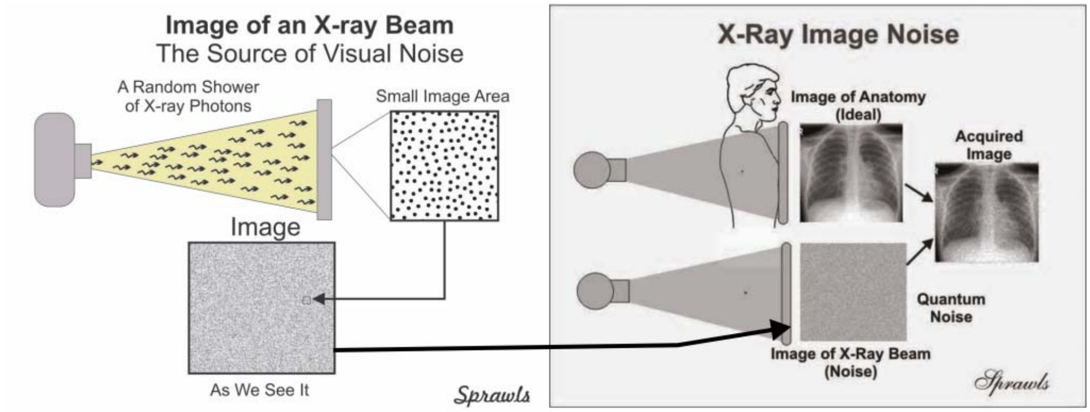


In digital radiography the pixel size must be considered along with the other sources of blurring, that is the focal spot and receptor layer that absorbs the X-radiation. An optimized design taking into consideration all factors would have a pixel size approximately the same as the blur from the other sources.

VII. Visual noise

After the discovery, Roentgen's extensive research documenting the many characteristics of the new radiation did not include the quantum structure consisting of individual photons. This is a highly significant characteristic because it is the major source of visual noise that can limit visibility in X-ray images. We can assume Roentgen did not see and discover this because he was using very high exposures to his receptors which minimizes noise.

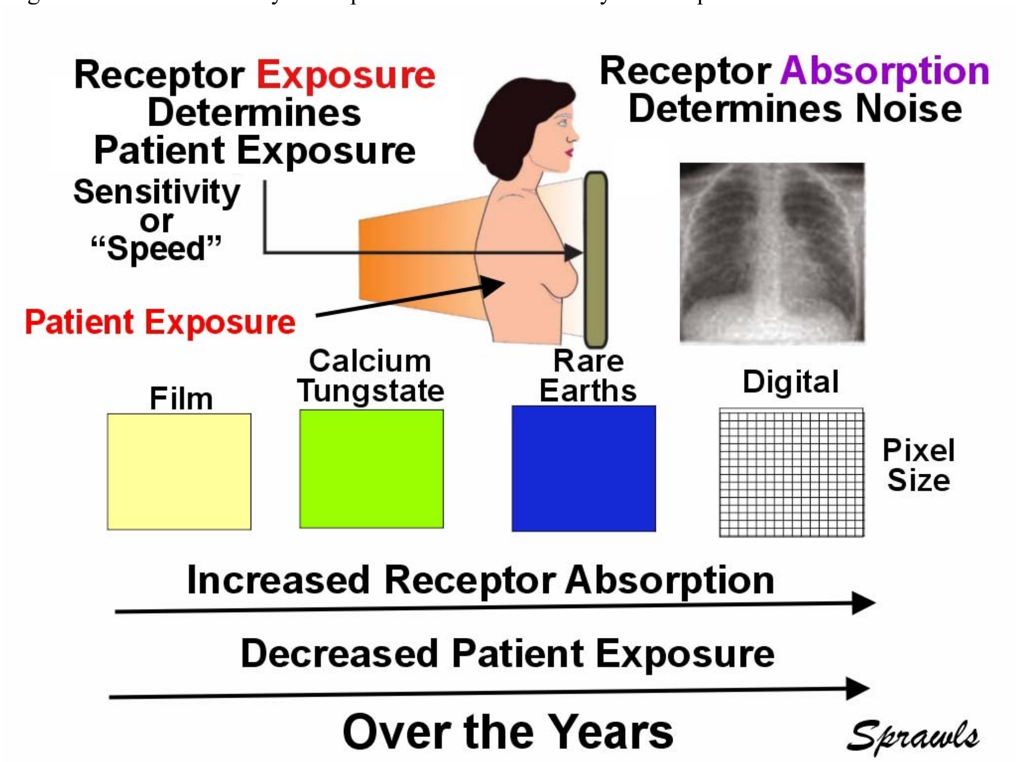
With X-ray imaging the so-called quantum noise is an image of the X-ray beam that is added to the image of the patient as illustrated here.



The clinical effect of visual noise is that it reduces the visibility of low-contrast objects in an image. This also includes small objects, like calcifications, because they are often with low contrast.

A continuing challenge throughout the history of X-ray imaging has, and continues to be, reducing the effects of noise on the visibility of the patient's body. As we recall, the visual noise is caused by the random statistical variation in the number of captured photons in small "sample" areas of the image. In digital radiography these are the image *pixels* and the *voxels* in CT. The noise, sometimes expressed as the standard deviation (SD) of the statistical variation among the pixels or voxels is inversely related to the exposure *captured* by the image receptor. For virtually all X-ray image receptors only a fraction of the exposure to the receptor is absorbed or captured and contributed to the formation of an image.

In X-ray imaging procedures the exposure to the patient is related to the required exposure to the receptor to produce an image. The image noise is determined by the exposure that is absorbed by the receptor as illustrated here.



Throughout the history of X-ray imaging research and development of new technology and methods have had two (2) major, and often conflicting objectives, increasing *visibility* and reducing radiation *exposure* to patients. This is often a factor in adjusting contrast sensitivity and visibility of detail but is especially significant in respect to visual noise.

The underlying factor is that X-ray image receptors do not absorb all the radiation they are exposed to. The exposure to a patient is related to the *exposure* to the receptor surface, the noise is related to the *absorbed* radiation, which is always less than the total exposure to the receptor.

Throughout the use of X-ray imaging there have been four (4) distinct phases relating to the absorption in the receptor and related patient exposure.

Film, the first receptor was a thin layer of photographic crystals and a very low X-ray absorption, this required very high X-ray exposures to produce the necessary image contrast. Because of the high exposure, quantum noise was not significant but noise from the grainy (crystals) structure of the film was.

Calcium Tungstate intensifying screens was the first major development reducing exposure to a patient. With this significant reduction in exposure noise could be seen in images. As described previously, screens were provided in three (3) types that varied in thickness to give a choice between visibility of detail and exposure to a patient. They all required about the same absorbed radiation to produce an image, and generally similar noise, but the thinner so-called "Detail" screens a higher receptor entrance and patient exposure.

Rare Earth intensifying screens were a revolutionary development because compared to Calcium Tungstate, they had higher *absorption* rates. A screen that could provide an image with the same visibility of detail and noise required lower entrance exposure and reduced patient exposure.

Digital receptors use a variety of different technologies and methods for producing images. In general, the materials used had reasonably good absorption characteristics, but another factor had to be considered, that was the size of the image pixels. Each pixel is a discreet sample, and it is the number of photons captured in each sample that determines the noise. Reducing pixel size to increase visibility of detail increases the noise because the number of photons captured is reduced.

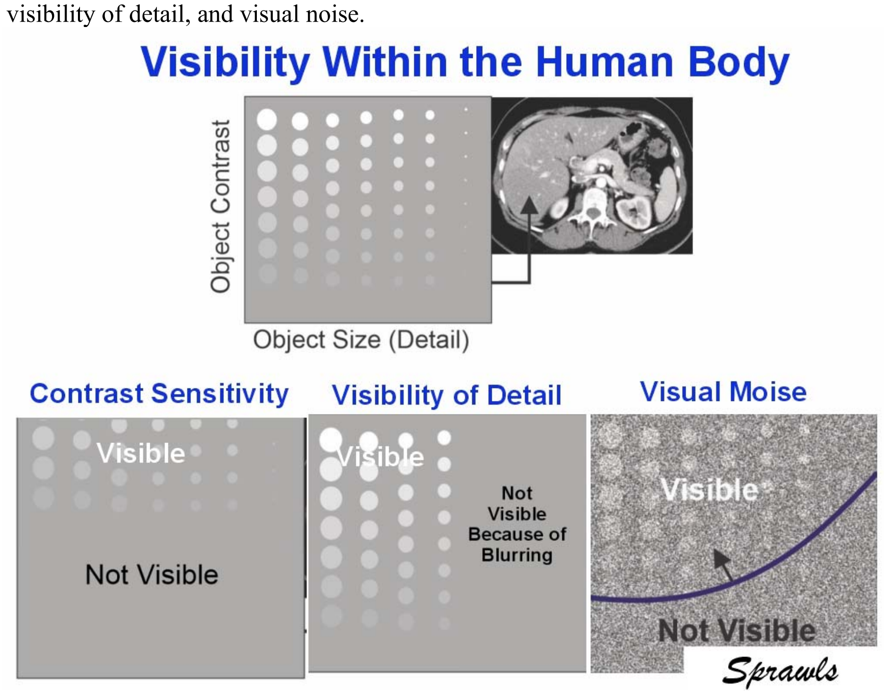
In all methods of digital imaging, radiography, CT, MRI, etc. this compromise between visibility of detail and visual noise must be considered when selecting pixel and voxel sizes for specific procedures.

An advantage with digital images is the possibility of mathematical processing to reduce the visible noise and is included in medical imaging systems.

Visual noise continues to be a factor to be considered in medical images but has been reduced over the years with advances in technology.

VIII. Overview and Conclusions

The discovery and extensive research by Prof. Roentgen on the characteristics and properties of "A New Kind of Radiation" quickly extended human vision into the human body and revolutionized the practice of medicine. From this beginning, many physicists, engineers, and medical doctors have collaborated to extend the scope of visibility to include many of the objects and conditions that were not visible in the early images. The visibility of a specific object depended on the relationship of its physical characteristics, contrast, and size, to three characteristics of the X-ray imaging process, contrast sensitivity, visibility of detail, and visual noise.



The two characteristics of the objects in the body can be represented by a diagram as shown to illustrate the factors affecting visibility.

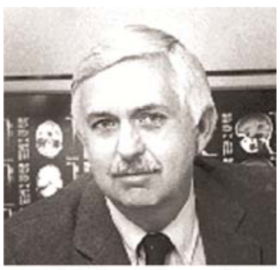
Following the introduction of X-ray imaging by Roentgen many inventions and developments have extended visibility to include many of the objects and conditions in the body.

Contrast Sensitivity of the imaging process determines the lowest contrast items in the body that can be visualized. The contrast between the soft tissues was the major challenge. Development of optimized X-ray spectra and film was a major contributor to increased visibility. Computed tomography (CT) extended visibility into the skull, which was the last major challenge.

Visibility of Detail, the small things, is limited by blurring within the imaging process. This was improved over the years with continuing developments of X-ray tubes with smaller radiation sources (focal spots) and receptors.

Visual Noise is a continuing challenge. It reduces the visible contrast between objects with low contrast in an image. A major factor is its conflict with reducing radiation exposure to patients. Noise is reduced by increasing the X-ray exposure *absorbed* in the receptor. It is the development of image receptors with increased X-ray *absorption efficiency* that has provided for the reduction of exposure to patients while maintaining the necessary image quality and Visibility.

ABOUT THE AUTHOR



Dr. Perry Sprawls

The career of Dr. Sprawls as a clinical medical physicist began in 1960 on the faculty of a large medical facility, Emory University Medical School and Clinics, and as a consultant for the medical imaging industry. During this time, he worked with and had experience with virtually all the new and developing imaging technologies and methods and clinical applications. It is this personal experience that is the foundation for much of this article and the several other articles that are referenced.

A major interest and activity now is working with other medical physicists to preserve and share our rich history and heritage. This includes serving as a founding Co-Editor of the International Medical Physics journal History Series.

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