THE SCIENCE OF MEDICAL IMAGING
AN INTRODUCTION TO THE QUEST FOR VISIBILITY

P. Sprawls

Emory University School of Medicine, Atlanta, and Sprawls Educational Foundation. www.sprawls.org

I. Introduction

The ability to investigate and visualize the interior of the human body is the major method for diagnosing many diseases, injuries, and evaluating conditions in the practice of clinical medicine. It is also valuable for guiding and monitoring treatment and therapeutic procedures. It is the medical specialization known as Radiology, Roentgenology, or generally Medical Imaging. Radiologists are the physicians with the education, training, and Board certifications who use the variety of medical imaging procedures in clinical practice. Medical physicists are the predominant scientists in the field of medical imaging and radiology, with activities including research and development, clinical collaboration, and provision of education for all professionals working with medical imaging.

Physics is the primary science of medical imaging. The overall medical imaging process is illustrated in Figure 1.

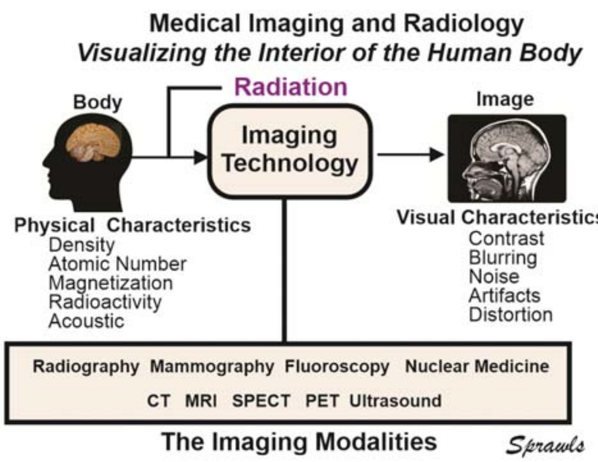


Figure 1. The elements of the medical imaging process.

The objective of a medical imaging procedure is to visualize some specific anatomical structure, object, or condition within the body. A medical image can be considered as a visual representation of some area of the human body, It is the process of converting physical characteristics of tissue within the body into visual characteristics within an image, as illustrated in Figure 1. The visibility of a specific item within the body depends on a combination of factors that must be considered in setting up and conducting an imaging procedure. The first is the selection of the modality, that is the type of equipment or technology to be used. The various modalities are identified in Figure 1. Each modality forms images using different physical principles and types of interactions with the tissue within the body. A distinguishing characteristic of a modality is the type of radiation used to penetrate and develop images through interactions with the tissue within a body.

The Imaging Modalities

Radiography, Mammography, and Fluoroscopy form images by projecting a beam of x-radiation through a body and producing "shadows" of internal structures and objects. The shadow images are formed by the varying attenuations of the x-radiation among the tissues that is determined by the physical characteristics of the tissue, especially physical density.

Nuclear Medicine includes a variety of procedures that uses radioactivity as the source of radiation. Radioactive substances are administered to patients and the gamma radiation from the body is imaged with a gamma camera. Nuclear Medicine using radioactivity also includes two of the tomographic modalities, SPECT and PET described below.

High-frequency, or Ultrasound, is a modality that has some specific clinical applications.

The differences among the modalities include the type of radiation used and the physical process used to form the images. Each modality has specific features, especially the characteristics of the images that determine visibility of specific conditions within the body, that make it "the modality of choice" for specific clinical applications. The choice of a modality for a specific clinical purpose--detecting breast cancer, for example, is the first decision a Radiologist makes. There are references for this, especially the Appropriateness Criteria published by the American College of Radiology (ACR).

Magnetic Resonance Imaging (MRI) is a tomographic imaging process that uses radio frequency (RF) signals to transmit information from the body tissues to the imaging system.

X-ray projection procedures (Radiography, Mammography, and Fluoroscopy) as well as the Gamma Camera, produce images of a body section. The chest is an example. All structures throughout the section produce shadows, with some overlying others. For many procedures this is not a problem and there is value in having one image that covers a complete anatomical region like the chest. However, there are advantages in having images of thin slices through a body section. This is *tomographic* imaging. The several tomographic modalities described below form images in two phases. The first phase is acquiring radiation data from a body, often referred to as "scanning." The second phase is mathematically "reconstructing" an image of slices within the body section from the data acquired during the scan..

The contemporary imaging modalities and methods available now are the result of over a century of research and development including the impact of the digital revolution. The results are imaging procedures with expanded *capabilities* for visualizing clinical conditions but also a major increase in *complexity*.

It is this *complexity* of the modern imaging procedures that requires a significant knowledge of the physics of the imaging process for the purpose of selecting imaging methods, evaluating image quality in relation to clinical requirements, and optimizing procedures with respect to image quality/visibility and potential risk to patients.

The Views

A distinguishing characteristic of a modality is the view of the human body it provides. There are two distinct views as illustrated in Figure 2.

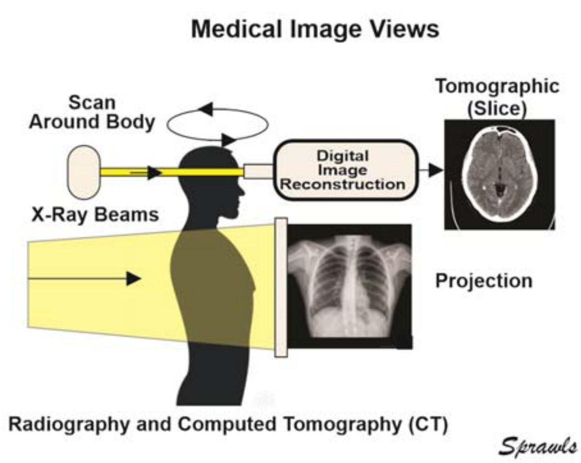


Figure 2. Comparing the two views of the human body, projection and tomographic.

II. RADIATION

All medical imaging procedures require the use of some form of radiation or energy that can both penetrate the body and interact with the tissues within the body to form an image. This is the reason for the name, Radiology, or Roentgenology honoring Wilhelm Roentgen, the discoverer of x-radiation, who demonstrated its medical imaging capabilities. *X-radiation* was the first and continues to be the predominant form of radiation for medical imaging. *Gamma* radiation from radioactive substances administered to patients is used in the Nuclear Medicine procedures with the gamma camera, single photon emission tomography (SPECT), and positron emission tomography (PET). Both x-radiation and gamma are form of ionizing radiation with potential biological effects (both good and harmful) to humans. The good is the use to treat cancer in the practice of Therapeutic Radiology or Radiation Oncology. There are potential harmful effects, generally related to the amount of radiation deposited in a body, that are considered in selecting and adjusting imaging procedures. Radiation Safety and Risk Management is one of the professional activities provided by physicists, generally designated as Health Physics.

Medical physicists are critical to this with their clinical activities focusing on maintaining image quality, risk management, as collaborators with radiologists and technologists, and as effective educators as required.

.

III. THE BIG PICTURE

The medical imaging process is a complex system of elements that interact to produce images with specific characteristics that determine visibility. The overview or "big picture" shown in Fig. 3 provides a framework and foundation for an understanding of the imaging process and how to optimize it for specific clinical purposes.

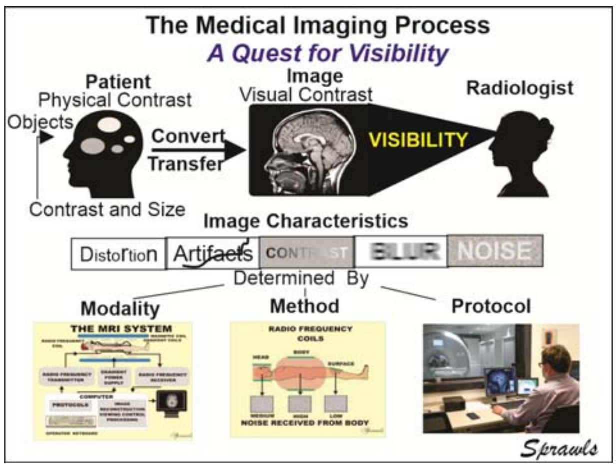


Figure 3. An overview of the medical imaging process and the many factors that determine visibility of specific conditions within the human body.

Most medical imaging procedures are a complex process with a combination of many variable factors that determine visibility of specific anatomical structures and clinical conditions. The radiologist is generally the professional with the responsibility for selecting and controlling the imaging procedure that is appropriate for a specific objective. This consists of first selecting a modality (MRI, CT, etc.) and an imaging method within the modality (Spin Echo, Inversion Recovery, etc.). The final step for each patient is the selection and adjustment of the *technique factors* (TR, TE, etc.) that form the *protocol* for the specific procedure. It is the combination of all these that determines the individual *physical characteristics* of images and the ultimate *visibility* of conditions within the body. It is the physical characteristics of the objects, structures, and conditions within the body that determine how they can be appropriately imaged (modality, method, and protocol).

IV. PHYSICAL CHARACTISTICS OF TISSUES AND FLUIDS WITHIN THE BODY

All medical imaging procedures are *physical interactions* between the imaging systems and the tissues and fluids within the body. The visibility of objects or conditions within a body depends on their physical difference, or contrast, relating to the surrounding area or background. Pathological conditions which are generally biological changes will be visible only if there are associated physical changes. For example, breast cancers are visible with mammography because they have an increased physical density in relation to the surrounding less dense tissue.

A major difference among the imaging modalities is the type of physical contrast that can be visualized.

X-Ray Imaging (Radiography, Mammography, and CT)

Radiography is the modality that produces recorded images by projecting an x-ray beam through the body and casting shadows of internal structures and objects. Typical radiographic images are shown in Figure 4.

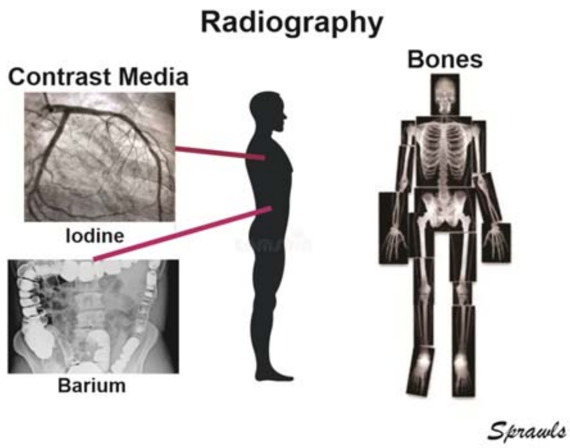


Figure 4. Radiographic images produced by natural contrast (bones) and administered contrast media (iodine and barium).

Radiography, including mammography, and fluoroscopy are projection imaging procedures in which an x-ray beam is passed through the body and casts shadows of internal anatomical structures and objects. All x-ray images, including CT, are formed by the difference in x-ray absorption/attenuation among the tissues. The two physical characteristics of tissue that determine x-ray attenuation are physical density and atomic number (Z). The effective atomic number (Z) of tissues, approximately 7.xx, has relatively little variation among the soft tissues and fluids in the body and is not a major source of contrast. It does contribute to the contrast and visibility of calcium and bones. The natural and often limited contrast among the soft tissue, fluids, and organs can be enhanced by administering substances, known as contrast media, during an imaging procedure as illustrated in Figure 4. The atomic numbers of iodine and barium enhance their x-ray attenuation and contribute to their effectiveness as contrast media. Compounds containing iodine are used for enhancing the visibility of blood vessels and the urinary tract. Barium is used for imaging the digestive tract including stomach and intestines. Differences in physical density are sources of contrast especially in the chest with the low-density air in the lungs providing a background for the bones, heart, and more dense lesions and cancers. Mammography is a special form of radiography for imaging the breast. It uses special types of x-ray beams to image the small differences in density within the breast, especially between the normal tissues and cancers.

Computed tomography (CT) is an x-ray imaging modality that has the capability to produce visible contrast among the small differences in density of the soft tissues, as in the brain. As illustrated in Figure 2, CT is a tomographic imaging procedure in which a thin x-ray beam is scanned around the patient in the plane of the slice of tissue being imaged. The beam measures the x-ray attenuation along many pathways or projections through the tissue slice. A computational process known as *image reconstruction* uses the attenuation data to produce an image that is a display of density differences among the tissues. The two great values of CT are the production of tomographic/slice images without interference from overlying anatomical structures and its high sensitivity for visualizing small differences among tissues.

Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) is a tomographic imaging process somewhat like CT but different in the physical tissue characteristics that are visualized. An MR image is an image of *magnetized* tissue. During the imaging procedure the tissues and fluids in the body are temporarily magnetized by a strong magnetic field. The level of magnetization of a specific tissue is determined by its hydrogen content, the only significant chemical element in the body with magnetic nuclei (protons) that align to produce the tissue magnetization. The concentration of hydrogen, or proton density (PD) is a characteristic of each specific tissue and a source of contrast. During the imaging process the magnetic nuclei are periodically flipped from their stable or relaxed direction. This is followed by a period of realigning or relaxation in relation to two different magnetic field directions, longitudinal and transverse. The times required for these relaxations, designated as T1 (longitudinal) and T2 (transverse), are characteristics of each specific tissue. This provides visible contrast among both the normal tissues, like gray and white matter in the brain, and between normal tissue and many pathological conditions…one of the great values of MRI.

Each MR image is an image of the *level of magnetization* in each tissue. However, the level of magnetization is constantly changing as the tissues go through the relaxation cycles. Therefore, the level of magnetization, or brightness of a tissue displayed in an image depends on "when the picture was snapped" during the relaxation cycle. This is determined by adjustment of factors in the imaging protocol. Generally, the imaging protocol can be set to produce images where each of the tissue characteristics, PR, T1, and T2 are the major source of visible contrast. It is the combination of the tissue characteristics and image protocol factors that determine the level of magnetization of each specific tissue and the resulting brightness in am image. Figure 5. compares MR and CT images and their sources of physical contrast.

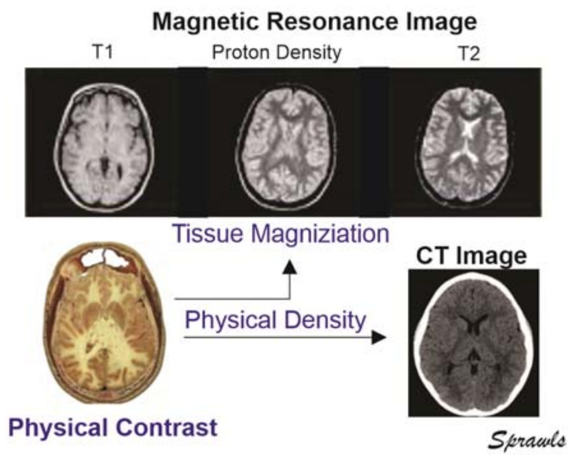


Figure 5. Two sources of physical contrast, density, and magnetization, that contribute to visibility of tissues.

Medical imaging is a physical process and can only produce images of the physical contrast within the body. There is naturally occurring physical contrast that provides for some visualization of most anatomical regions and organ systems of the body. When that is not adequate different forms of contrast media can be administered to enhance visibility of structures (GI track, blood vessels, etc.) and pathological tissues.

Radionuclide Imaging (Nuclear Medicine)

A form of *physical contrast* can be created in the human body with the administration of a radioactive substance that selectively concentrates in different tissues relating to conditions, especially pathologic, and function such as blood perfusion in the myocardium or metabolic activity in the brain. A variety of radionuclides are used. Images displaying the distribution of radioactivity in an anatomical region or organ are produced with three specific modalities.

The *gamma camera*, as the name implies "takes a picture" providing visibility of radioactivity in the body.

Single Photon Emission Tomography (SPECT) uses a gamma camera that is rotated around the patient's body and uses image reconstruction to produce tomographic images. It is a form of computed tomography using radioactivity as the contrast to be imaged. Positron Emission Tomography (PET) is also a tomographic method that provides visibility of radioactive nuclides that emit positrons that can be used to image metabolic activity. These three modalities are compared in Figure 6.

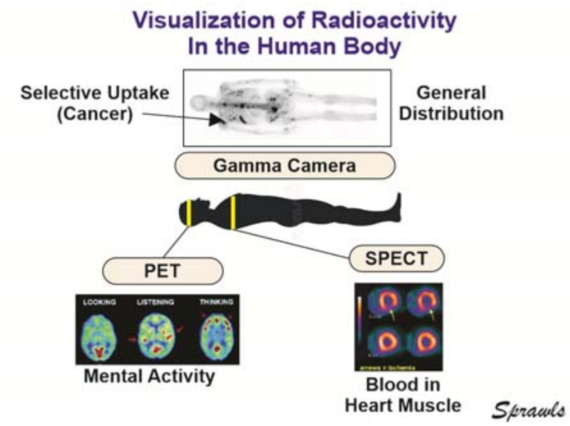


Figure 6. The three imaging modalities for visualizing radioactive pharmaceuticals that have been administered to a patient.

A major distinction is that the gamma camera views a large section of the body, like a photographic camera, and produces an image of the radioactivity through that section. Both PET and SPECT are tomographic imaging methods producing images of selected slices.

Ultrasound Imaging

High-frequency sound, ultrasound, can be used to produce images within the human body with two types of interactions. One is by reflections from structures within the body that produce echoes; the other involves Doppler shifts in the frequency of sound produced by the motion of flowing blood. These are illustrated in Figure 7.

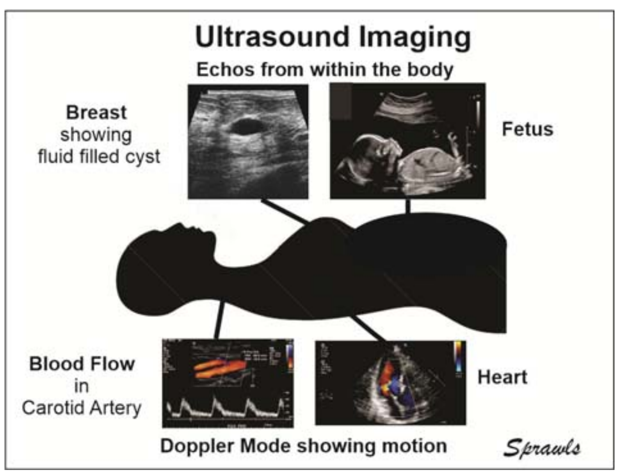


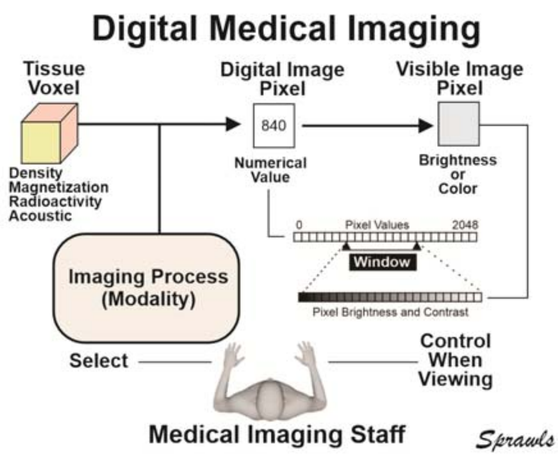
Figure 7. Images produced with ultrasound with the two modes: echoes from reflecting structures and visualization of flowing blood using the Doppler effect.

An ultrasound image is a display of structures or objects within the body that reflect the sound pulses transmitted into the body. Reflections occur at surfaces or boundaries between tissues that have different acoustical properties, especially the speed of sound. Most organs and tissues within the body are a mixture with different characteristics and produce echoes that are visible in an image. An exception is a clear fluid like water that does not produce echoes. This is illustrated in the image of the breast where the fluid-filled cyst does not produce echoes and appears as a “black hole”. This is especially valuable for distinguishing fluid filled cysts from tissue masses that could be cancer. Ultrasound is the preferred method for imaging fetuses before birth. It is a quick and easy procedure as it does not use ionizing radiation, x-rays, with a potential risk.

V. DIGITAL IMAGES AND IMAGE STRUCTURE

Virtually all medical imaging modalities produce images in a digital format, very different from images on film as in the past. There are many values and advantages with digital images, like digital photography that we all use, easy to adjust, store, and send to others. However, the structure and numerical dimensions of digital images have a major effect on the several image quality characteristics and visibility. The digital image *numerical dimensions* are often some of the procedure protocol factors that can be adjusted to optimize the image quality and visibility for a specific patient procedure.

There are two distinct functions that occur in the production of digital medical images with all the modalities. One function is creating a numerical value for the tissue characteristic that is being imaged and the other is the formation of an image displaying these numerical values over the viewed section of the body. The difference among the modalities is how these functions are performed. Here we consider the common characteristics that apply to all modalities. The first, developing numerical values for the tissue characteristics, is illustrated in Figure 8.



.
Figure 8. The two phases of creating a visible image displaying the physical characteristics of tissue within the body.

The first phase is the acquisition of the data from the body, often referred to as “scanning” and the creation of numerical values, a digital image. The common function of all imaging modalities is that the body is divided into small cubes of tissue, voxels, and the physical characteristic of the tissue is measured, with the value recorded in a corresponding area in the image, a pixel. Which tissue characteristic is being imaged is determined by the modality selected by the medical staff. The second phase that can take place later is the viewing of the digital image by the radiologist or other medical professional. When viewing a digital image, the conversion of the digital image into a visible image can be controlled to emphasize the visibility of specific objects and areas within the body. The primary control is the “window” that selects the range of digital values that will cover the brightness range in the visible image.

The other function within an imaging procedure is the formation of the tissue voxels into a matrix, typically representing a slice of tissue within the body, and a corresponding image as a matrix of pixels as illustrated in Figure 9.

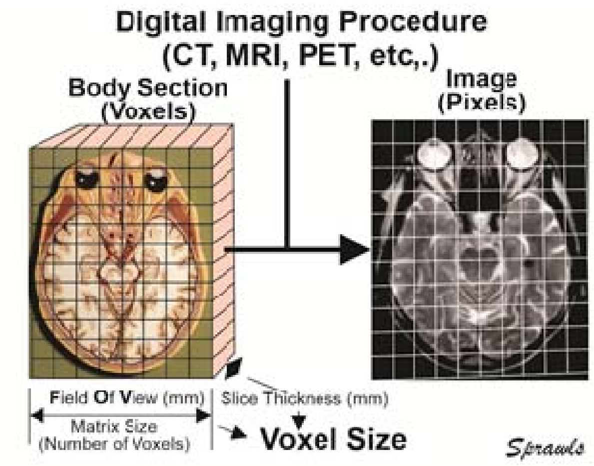


Figure 9. The dimensions associated with a digital image that affect image characteristics and visibility.

All the medical imaging procedures that produce digital images begin by dividing the area of the human body that is to be imaged into a matrix of small cubes known as "volume elements" (voxels). The image is formed as a matrix of "picture elements" (pixels). The size of the voxels is a major factor determining the quality characteristics of the image, especially the blurring and visual noise.

Each voxel can be considered as a discrete "sample" of tissue. In general, the imaging process measures a physical characteristic of the tissue (density, magnetization, or radioactivity) and calculates a numerical value. The numerical value is then displayed in a corresponding image pixel as a brightness. For example, in a CT image the brightness of each image pixel is determined by the physical density of the tissue in the corresponding voxel. In MRI the brightness of a pixel is determined by the magnetization of the tissue in the corresponding voxel.

Our interest here is the effect of voxel size on the quality characteristics of the image. As illustrated, the size of a voxel is determined by three (3) dimensions as shown. These dimensions are established for each of the imaging modalities in relation to the physical characteristics of the imaging equipment and the imaging process. Generally, with each modality, the dimensions, especially slice thickness, can be adjusted or "fine-tuned" when setting up the procedure protocol for a specific patient.

The significance of the dimensions of the digital images, the voxels, and pixels, is that they are major factors determining the quality characteristics and visibility with specific images. They must be selected and adjusted to provide appropriate visibility with each medical imaging procedure. It is not a simple process because of the conflicting effects on image characteristics and visibility that some of the dimensions have and the necessity to develop *optimized imaging protocols* for specific patient procedures, an application of physics to clinical medicine.

VI. Image characteristics that determine visibility

The visibility of specific anatomical structures, objects, or conditions within the human body is determined by a combination of image characteristics as illustrated in Figure 10. These characteristics and the resulting visibility are determined by a complex combination of factors including which *modality* is selected, the imaging *method* within the modality, and the adjustment of the specific imaging *protocol* with respect to the *technical factors* adjusted for the procedure. The objective here is to consider the individual image characteristics and their effect on visibility. This is the fundamental science of medical imaging.

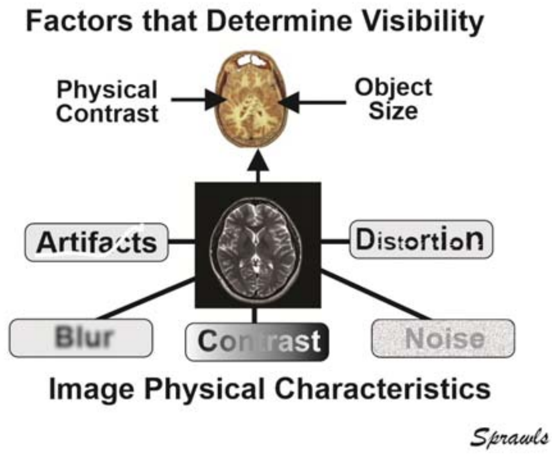


Figure 10. The combination of image characteristics that determine visibility of objects within the body.

Visibility is a goal of all imaging procedures, ranging from normal human vision to the use of satellites orbiting the earth. Many forms of technology--microscopes, telescopes, television, etc.--are used to extend the range of human visibility to see objects that are invisible because of conditions including size, distance, enclosures, and other characteristics and composition of the objects. Medical Imaging Systems are the technology used to extend human vision into the human body. As described before there are a variety of technological systems, the *modalities*, used in modern medical imaging procedures. As illustrated in Figure X, it is the choice of modality, the imaging method within the modality, and the adjustment of protocol technical factors for each patient procedure that determine the physical characteristics of an image and visibility.

There are five (5) fundamental characteristics of images as illustrated in Figure 10 that collectively determine visibility of specific objects within the body. It is a complex process because of potential conflicting relationships among the characteristics and dependence on factors including limitations of the technology, radiation exposure to patients, and the time required to produce images.

The fundamental science of medical imaging, physics, is built on an understanding of the physical characteristics of images and their relationship to visibility.

VII. Image contrast and procedure contrast sensitivity

Contrast means *difference*, the difference between and among items, and is the fundamental characteristic of an image. Within an image an object is visible only if it is *visually different* with respect to the surrounding area or background, either in brightness or color. Without contrast there is no image. The contrast contributing to visibility originates as physical contrast within the body as physical differences among tissues or objects to be visualized as described previously. The imaging process converts the physical contrast and transfers it to an image as visible contrast as illustrated in Figure 11.

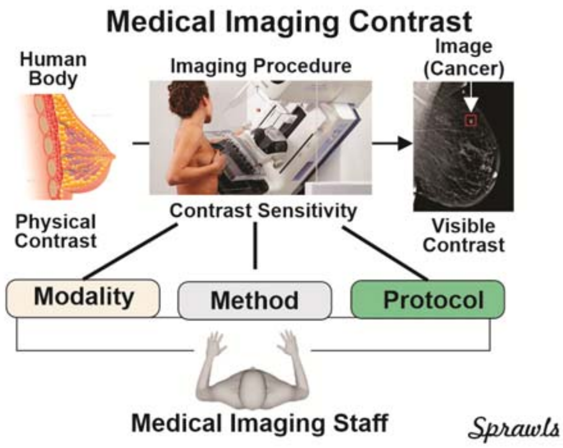


Figure 11. The factors that determine and control the visible contrast in a medical image.

The objective is not to produce as much image contrast as possible; it is to produce sufficient contrast for the desired visibility. The transfer of *physical contrast* in the body to *visible contrast* in the image is determined by the *contrast sensitivity* of the imaging procedure. Contrast sensitivity is the major characteristic of an imaging procedure for visualizing specific objects or conditions within the body. A cancer in the breast is the example used here. The contrast sensitivity is determined first by the selection of an appropriate imaging modality and method, and then adjusting the technical protocol factors for the specific patient.

The contrast sensitivity of an imaging procedure determines the lowest physical contrast within the body that will be visible as illustrated in Figure 12.

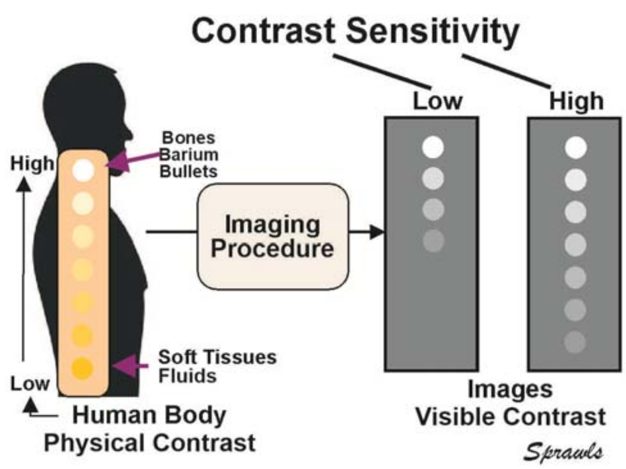


Figure 12. The concept of contrast sensitivity: the characteristic of an imaging procedure that determines the visibility of objects with the lowest physical contrast within the body.

It is not difficult to produce visible images of high-contrast objects in the body, such as bones, bullets, etc. The continuing challenge is to develop procedures to visualize the low contrast objects, especially the soft tissues and fluids. Mammography is the modality that has developed over the years with innovations to enhance contrast sensitivity and the visibility of cancers. A major innovation in medical imaging was the invention and development of computed tomography (CT) that provided visualization of the soft-tissue brain within the dense skull as illustrated in Figure 13.

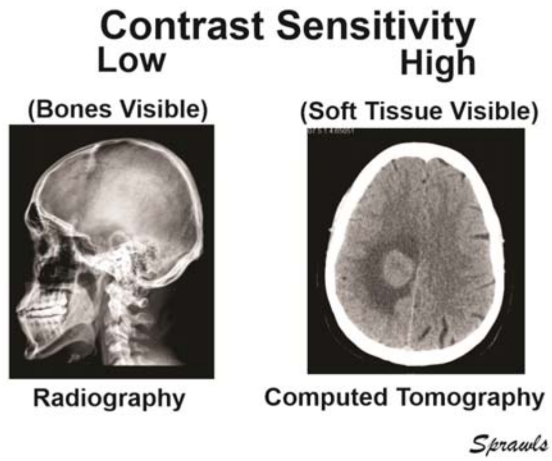


Figure 13. Comparing the contrast sensitivity of two x-ray imaging modalities, radiography and computed tomography (CT).

Radiography produces images by projecting an x-ray beam through the body and casting shadows of objects with high physical contrast, especially the bones. As illustrated in the image above low-contrast soft tissue brain is not visible in the radiograph. However, with CT, which is also an x-ray imaging process, the low physical contrast among the soft tissues, and especially diseased tissues like the tumor, is visible. This high *contrast sensitivity* is the major characteristic of CT that contributes to its value for viewing soft-tissue organs throughout the body. The combination of two factors contributes to this. It is a tomographic process as illustrated in Figure 2 that displays images as thin slices without looking through bones and it uses digital image processing as illustrated in Figure 14.

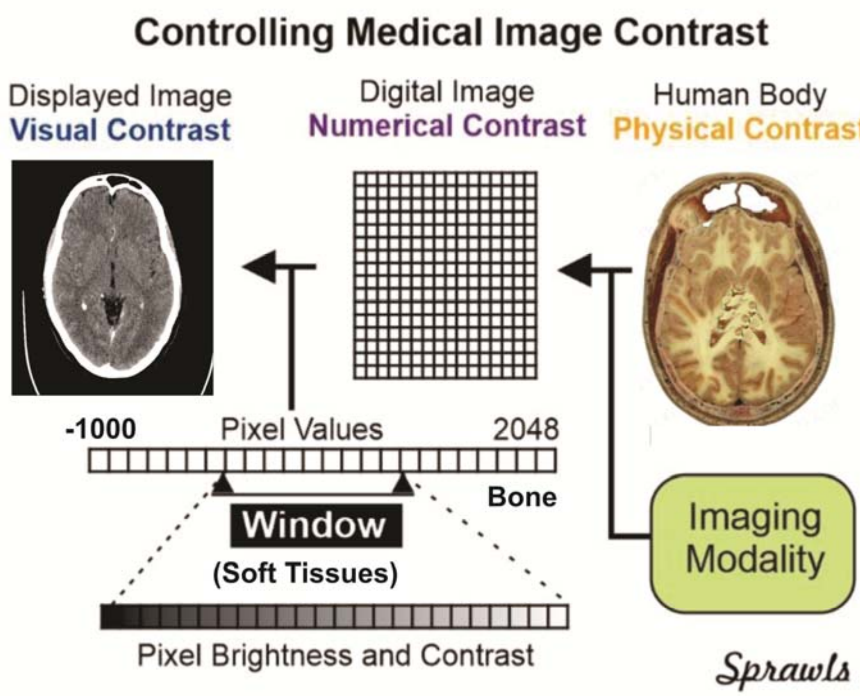


Figure 14. Using digital image processing to provide high contrast sensitivity and control image contrast to enhance visibility.

Computed tomography first creates a digital image by the process of mathematical image reconstruction from data collected on the attenuation of x-ray beams passing through slices of the human body. The numerical value of each pixel is determined by the physical density of the tissue in the corresponding voxels. The pixel values cover a wide range from low-density air (-1000) to high-density bone (2048). The soft tissues and fluids cover a small range within the large range. As shown, when a digital image is being displayed and viewed, the range of pixel values that will cover the brightness range (from white to black) is adjusted with "window" control. With this, the relatively small range of soft tissue densities and physical contrast can be displayed over a large brightness range and visible contrast.

The ability to control the window when viewing medial digital images provides the opportunity to adjust and optimize the contrast and visibility of various anatomical objects and regions within an image.

Medical physicists evaluate the contrast sensitivity of medical imaging procedures with test devices/phantoms that contain a series of objects with varying physical contrast and determining the lowest physical contrast that is visible. One of these will be illustrated later.

As described and illustrated previously each of the modalities visualizes different forms of physical contrast, tissue density, tissue magnetization, radioactivity, etc. The contrast sensitivity of the imaging process determines the lowest level of physical contrast that can be visualized. This is especially significant because the physical contrast, especially among the soft tissues which have almost similar density values, is often very low. Mammography is a special type of radiography that has been developed to have a high contrast sensitivity. Within a *modality* there are typically a selection of *methods* that can be used. With modern mammography there is the choice of views, and either projection or tomographic imaging which affects contrast sensitivity. Then for each patient there are various technical, or technique factors that are adjusted often depending on the size of the patient or specific clinical needs. The selection and adjustment of these factors establish the procedure *protocol* for each patient. The number of factors in a protocol for a specific patient can range from just a few for radiography to perhaps 20 or more for the much more complex imaging modalities like MRI.

Medical physicists provide the scientific and technical knowledge and experience needed to ensure adequate contrast sensitivity and visibility for imaging procedures. This is through research and development of imaging technology and methods, evaluation of equipment performance (quality control and assurance), collaboration with physicians and imaging staff attempting to optimize procedure protocols, and especially to provide educational opportunities for the other medical imaging professionals. In these activities physicists use a variety of test objects, often referred to as phantoms, to measure and evaluate contrast sensitivity. This will be illustrated later.

VIII. BLURRING AND VISIBILITY OF DETAIL

With all forms of imaging, including human vision, the size of objects affects and limits their visibility. This is generally designated as *visibility of detail*. It is the *blurring* that occurs during an imaging process that limits *visibility of detail*. The reality is there is some amount of blurring in all imaging procedures, including human vision. It is the blurring within our visual system, that often increases with age, that limits the visibility of small print and other small objects--that is, visibility of detail. This characteristic, visibility of detail (the medical term is visual acuity), is tested with a chart shown in Figure 15.

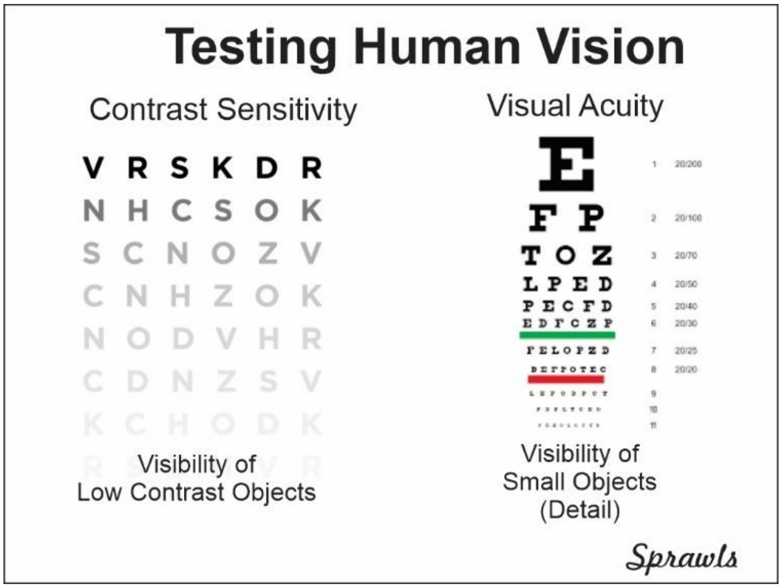


Figure 15. A chart used to test the two factors, contrast sensitivity and blurring, that limit visibility in relationship to the objects being viewed, their contrast and size.

Blurring, which is present in all imaging systems, from the human eyeball to satellites circulating and viewing the earth, limits visibility of objects in relationship to their size, often referred to as image detail. In optical systems cameras, projectors, etc., blurring is generally caused by inadequate focusing of the lens. There is some blurring that occurs in all medical imaging procedures and is the factor that limits the visibility of small objects and structures, or detail in the body. This is a significant factor because it determines which objects and structures can be viewed and the clinical procedures that can be performed with each of the imaging modalities. An example, mammography, is illustrated in Figure 16.

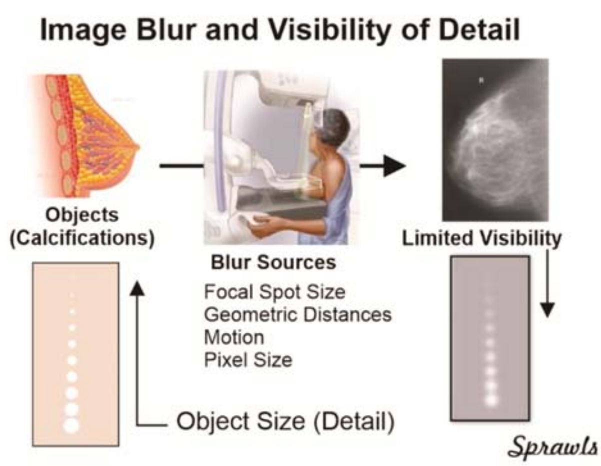


Figure 16. Sources of blur and effect on visibility of small objects and detail within the body.

The blurring with each imaging modality is determined by the physical design of the equipment and the process for producing the images. In mammography, where the image is produced by projecting an x-ray beam through the breast, the size of the x-ray source (the x-ray tube focal spot) and the distances within the setup are sources of blur along with any motion of the patient during the formation of the image. Of all the imaging modalities, mammography is designed to produce images with the least amount of blurring. This is because a valuable sign of breast cancers are small, micro-calcifications (approximately 0.15 mm) that need to be viewed for a diagnosis, A significant source of blurring with all imaging modalities that produce digital images is the size of the tissue voxels and image pixels. Voxel and pixel sizes are design characteristics of each modality and can often be adjusted within each modality through three protocol technique factors: anatomical field of view, matrix numerical size, and slice thickness for the tomographic imaging procedures. This is illustrated for mammography in Figure 17.

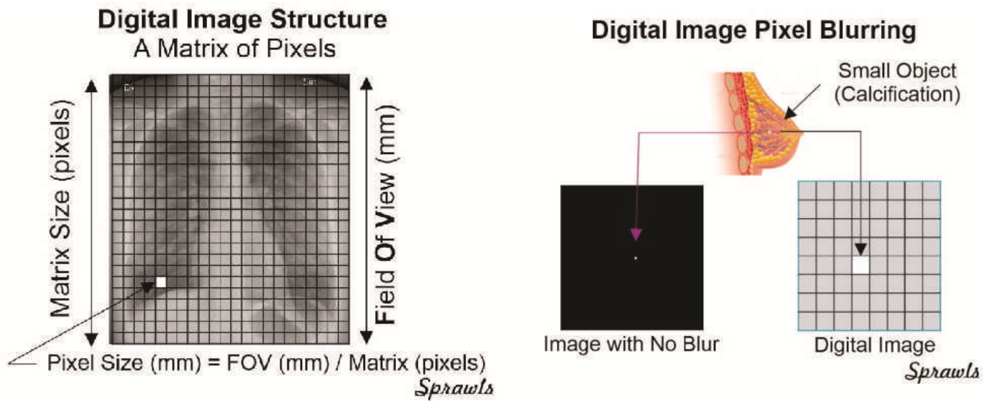


Figure 17. Factors that control pixel size and the blurring produced by pixels in a digital image.

A tissue voxel or image pixel is a blur because all objects or structures within it are mixed or blurred together and represented by one numerical number.

A defining characteristic of each medical imaging modality is its inherent blurring and visibility of detail it can provide as compared in Figure 18.

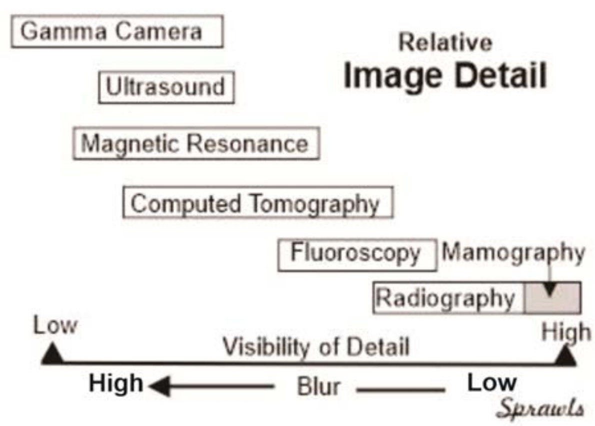


Figure 18. The relative visibility of detail provided by the imaging modalities.

The general visibility of detail (amount of blurring) with each modality is determined by the design of the equipment and how the images are produced. For each modality, computed tomography (CT) for example, there is a range of blur values and visibility of detail that can be provided. There is the selection of specific *methods* within a *modality* and especially the adjustment of the *technique factors* to establish the imaging protocol for each patient. The visibility of detail for a specific image is determined by the combination, or composite of the several sources of blur within the imaging procedure. In principle, the blurring and resulting visibility of detail can be adjusted over a relatively wide range for each imaging modality is illustrated in Figure 19.

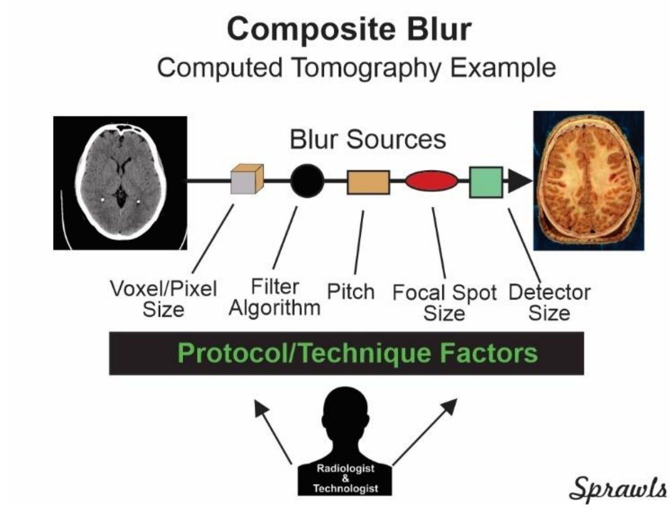


Figure 19. An example of the factors that can be used to adjust the blurring and visibility of detail in a specific imaging procedure.

That raises a question. If the blur is adjustable, why not set it to the lowest value so that images provide maximum visibility of detail? As described later, many factors that affect blurring also affect other image characteristics and the radiation exposure to patients. These are often opposing factors. Changing a factor to *reduce blurring* can *increase visual noise* resulting in less overall visibility and image quality.

The imaging protocol for a specific patient procedure should be *optimized* to provide an appropriate balance among the image characteristics and other factors including radiation exposure to the patient. Medical physicists provide the knowledge and experience to support this process.

IX. VISUAL NOISE IN IMAGES

We are most familiar with audio noise--sounds that interfere with our hearing and often are distracting and perhaps irritating. There are other types of noise in other forms of communication including electronic signals. Our interest here is *visual noise* that interferes with *visibility* in medical images. Visual noise is an image of *random objects*, specs, or spots, superimposed over the image that is to be viewed. It is sometimes known by other names, including grainy or mottle. In medical imaging there are two major sources of visual noise. In the modalities using x-radiation or radioactive materials (so-called ionizing radiation) it is the random nature of photon production and interactions. In MRI that uses radiofrequency (RF) signals to acquire images from the human body, noise is produced by stray RF energy created by thermal activity with the body tissue.

The specific effect of visual noise is to *reduce visibility* of low-contrast objects within an image as illustrated in Figure 20.

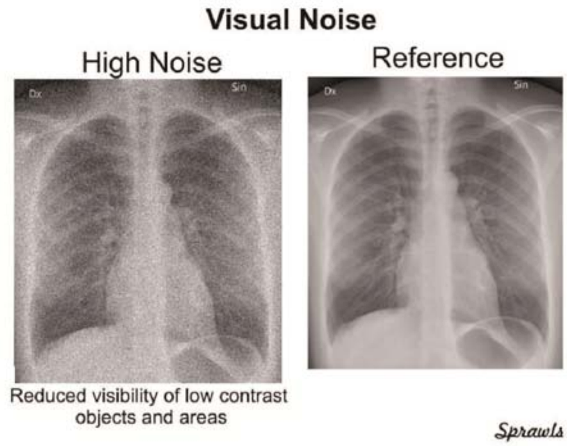


Figure 20. The effect of noise on visibility in an x-ray image.

Visual noise is an image characteristic that limits visibility of certain objects or structures within the body. Specifically, it reduces and limits visibility of objects that have low visual contrast. This is typically within the soft tissues and organs within the body and not with imaging the high-contrast bones. Some level of noise is in all x-ray images but can be controlled. The noise is an image of the x-ray beam itself that in added to the image of the patient anatomy as illustrated in Figure 21.

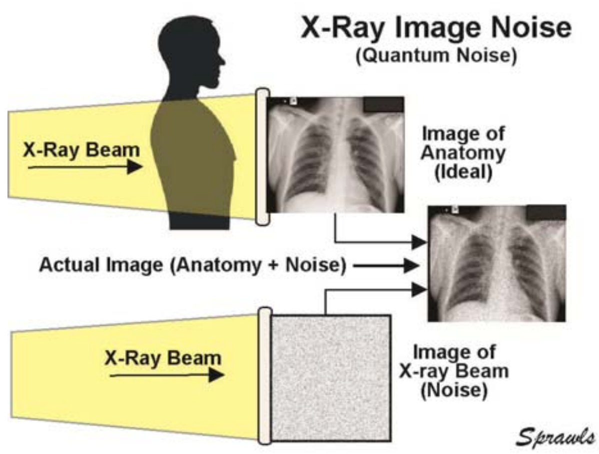


Figure 21. The source of noise in an x-ray image.

The control of the noise in an x-ray image is by adjusting the intensity (exposure) of the x-ray beam which determines the natural random distribution of the x-ray photons within the beam as illustrated in Figure 22.

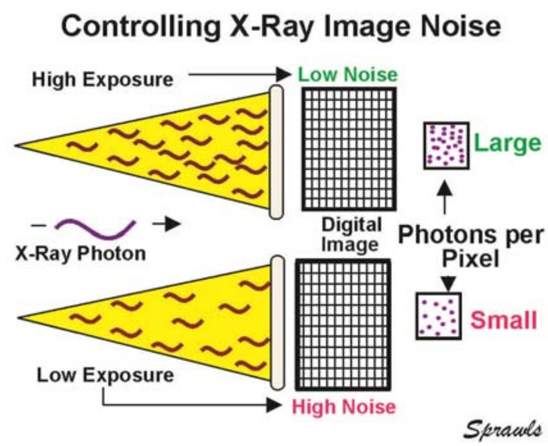


Figure 22. The relationship of x-ray image noise to the intensity of x-ray beam (exposure) forming the image.

This is perhaps the most significant factor in the physics of medical imaging because it affects two of the image characteristics that control visibility (blurring and noise) and the amount of radiation (dose) deposited in a patient's body. It is the factor that requires physics knowledge and experience in *optimizing imaging procedures* for maximum benefit for individual patients.

X-radiation and radiation from radioactive materials used for imaging is in the form of small units (quanta) of energy, photons. An x-ray beam can be considered as a "shadow" of individual photons, as rain is a shadow of individual drops of water. The significance is they are randomly distributed with respect to both area and time. Consider the example in Figure 16 where a digital image is formed by exposure with a "uniform" x-ray beam. The reality is at the atomic scale level an x-ray beam is not uniform but has a non-uniform and random distribution of the photons. In the formation of a digital image this results in a random distribution of the *number of photons* captured in each pixel. This produces a random variation in the brightness of the displayed pixels in the image which we see as visual noise as shown in figure 23.

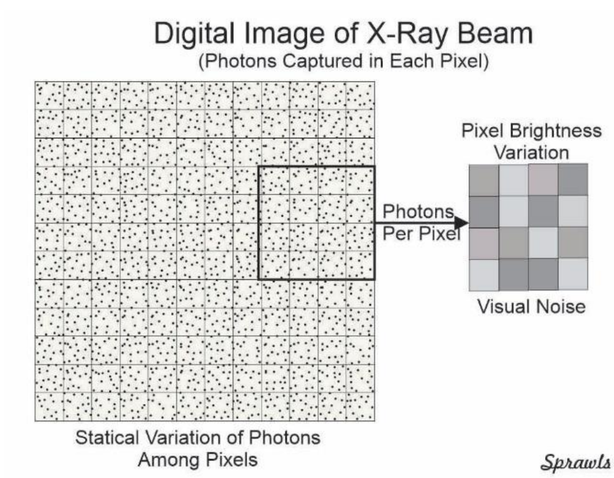


Figure 23. The source of visual noise in an x-ray image.

This statistical variation which appears as noise is *inversely related* to the average number of photons captured in each pixel, or in each voxel for tomographic imaging procedures. With knowledge of the statistics, it is possible to control the noise in images and set it to a level that is appropriate when considering other factors, especially radiation exposure to patients. The statistical distribution is shown in Figure 24.

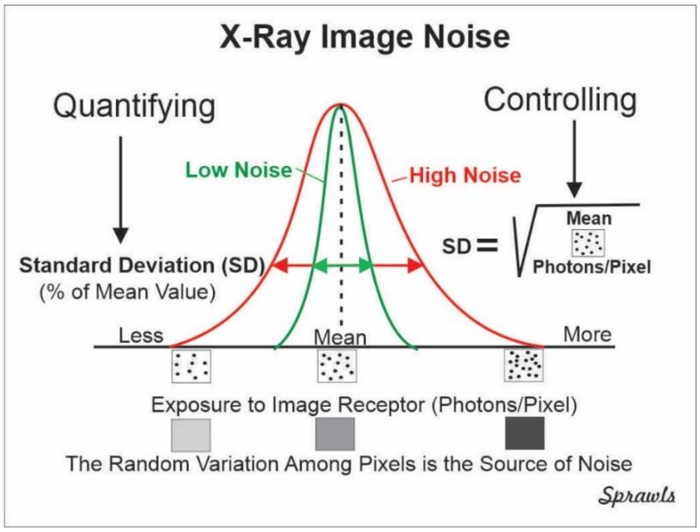


Figure 24. The relationship of the random variation of photons among pixels (the source of noise) and the average number of photons (exposure) in each pixel.

The variation of photons among the pixels follows a statistical *Gaussian distribution* with a specific property. The variation that is the source of the noise is inversely related to the number of photons forming each pixel in the image. This makes it possible to both quantify or calculate the noise and control it in an image.

In a Gaussian distribution the spread or distribution of photons can be calculated and expressed as the statistical quantity, Standard Deviation (SD), The value of the SD is the mathematical square root of the average number of photons per voxel as indicated in Figure 24.

The significance of this is that the noise in x-ray and radionuclide images can be controlled by adjusting the exposure to the imaging system which also affects the exposure to patients. A major decision that must be made in selecting imaging modalities and methods along with adjusting the technical factors in the protocol for specific patients is to achieve an appropriate balance between *image visibility* and *radiation exposure* to patients. For the modalities that produce images in a digital format, which is the majority that are used now, it becomes a complex issue because image blurring becomes a factor. This is because of opposing effects of voxel/pixel size on both visibility of detail (blurring) and visual noise as illustrated in Figure 25.

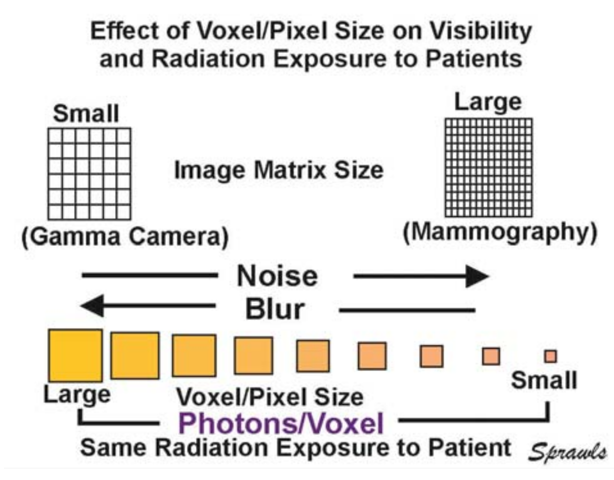


Figure 25. The opposing effect of voxel/pixel size on two factors determining visibility, blur and noise

The size of tissue voxels and corresponding image pixels varies over a large range for the imaging modalities. The factor that accounts for most of this variation is the numerical size of the image matrix. This is first determined by the design of the imaging equipment for each modality and can then be adjusted some by the imaging staff when setting up the procedure protocol for a specific patient. The voxel size directly affects the image characteristics as illustrated here. It indirectly affects another major factor--the radiation delivered to the patient's body.

When voxel size is reduced to reduce blur and improve visibility of detail the noise will be increased because the smaller voxel will capture less photons. This will require an increase in the radiation exposure to reduce the noise to an acceptable level. These are the three factors that are taken into consideration in the design of optimized procedure protocols for patients. This applies to all imaging modalities using x-radiation and radiation from radionuclides.

Visual noise is a significant factor affecting visibility with magnetic resonance imaging (MRI) but the source is different from the other imaging modalities. With MRI radiofrequency (RF), signals transmit the tissue characteristics from the body to produce an image. Unfortunately, the thermal activity within the human body generates some random RF energy that appears as noise in images as illustrated in Figure 26.

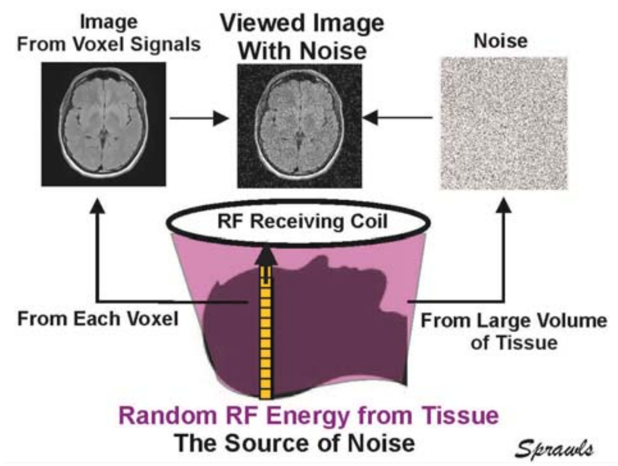


Figure 26. The source of visual noise in MRI.

Magnetic Resonance images are produced by receiving and processing radiofrequency (RF) signals from each tissue voxel that provides a measure of the tissue magnetization at that specific time in the imaging process. These signals are stimulated (and are like echoes) by RF pulses transmitted into the body during the imaging procedure. The intensity of the signal from each voxel determines the brightness of the corresponding image pixel. Unfortunately, some low-level RF energy is generated by the thermal activity within the human body. This random RF energy is also received by the imaging system and appears in the image as noise as illustrated in Figure 26.

The quality of the image and visibility of the tissues is determined by the ratio of the *signal to noise* strengths. The visibility of the noise is reduced by increasing the *signal to noise* ratio. Actions to achieve this including larger voxels, stronger magnetic fields, the special design of the RF receiving coils, and the collection and averaging of a larger quantity of RF signals with extended imaging procedure times. Some of these (magnetic field strength) are determined by the design of the equipment but most are factors that can be changed and adjusted when setting up the procedure protocols for specific patients.

X. IMAGE ARTIFACTS AND DISTORTION

Contrast, blurring, and visual noise are characteristics that apply to *all medical images* and collectively determine visibility of the objects and structures within the body that are important for medical diagnosis. There are two other image characteristics, artifacts and geometric distortion, that are not in all images but are generally undesirable. When artifacts are present, they generally do not reduce overall visibility within the image but are distracting and might cover some objects or areas. Some examples are shown in Figure 27.

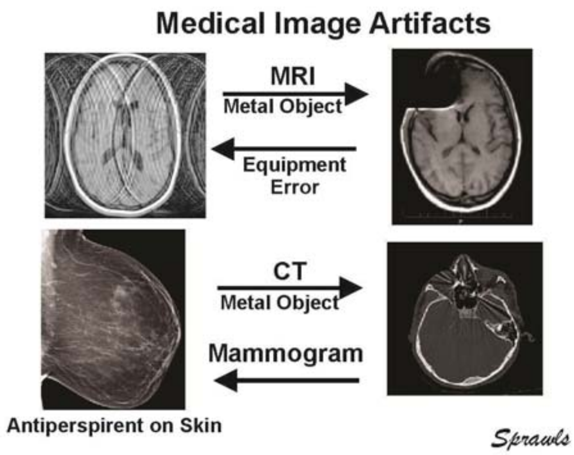


Figure 27. Some example artifacts that appear in medical images.

Artifacts are features that appear in an image that are not caused by the body anatomy itself. Artifacts are sometimes referred to as "ghosts" and not representing actual objects or structures. In general, the types and sources of artifacts are specific to each of the imaging modalities relating to how the images are produced. With radiography and mammography where an x-ray beam is projected through the body, non-anatomical objects in the path of the beam, both internal and on the surface, produce shadows that appear in the image as artifacts. While many will be recognized and identified for what they are, some can be mistaken and incorrectly diagnosed for signs of a disease. An example in Figure 21 are small pieces of an antiperspirant cosmetic, On the surface of the body they can appear as abnormal and medically significant objects within the breast. Implanted metal objects within the body are common sources of artifacts in both MRI and CT because they interfere with the imaging process, usually appearing as white streaks or dark areas. For both MRI and CT where data to create the image is acquired over an extended time, movement by the patient, including breathing, during this time distorts the data and can produce artifacts in the image. Within the imaging modalities there are a variety of techniques and actions that can be taken to reduce specific artifacts.
Distortion is a characteristic of an image in which the size and location of objects and structures are not accurately displayed. The most common is in radiography where there is geometric magnification of objects at different depths within the body which will be magnified differently.

XI. EVALUATING IMAGE CHARACTERISTICS AND VISIBILITY

As described above visibility in a medical image varies over a large range and can be controlled by the selection of imaging modalities, methods within a modality, and the adjustment of technique factors for the procedure protocol for specific patients. To provide appropriate visibility with imaging procedures it is necessary to evaluate or measure visibility and the effects of the variable image characteristics, contrast, blurring, and noise.

Radiologists generally do this based on their experience in viewing many images and their judgment on image characteristics appropriate for specific clinical procedures.

Medical physicists use a more scientific method by producing and analyzing images of test devices or phantoms. One such device is illustrated in Figure 28.

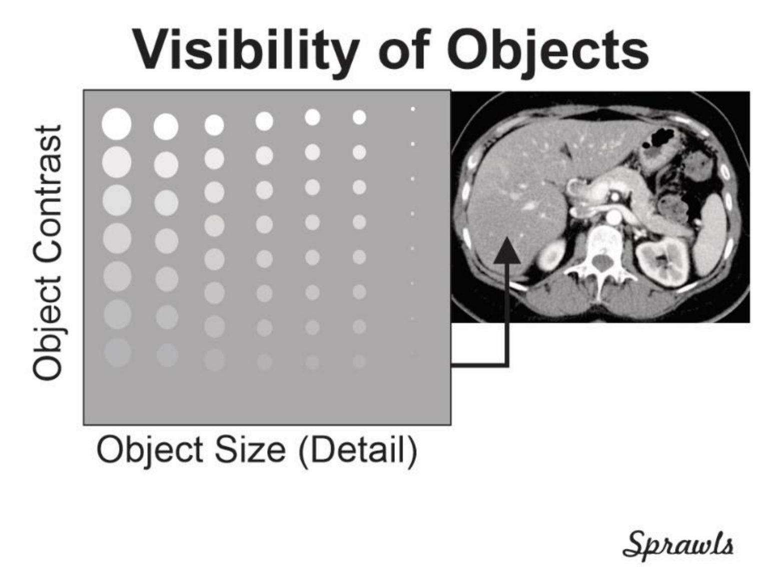


Figure 28. A Contrast Detail test device or phantom (shown on the left) contains objects with varying contrast and size/detail to represent the range of objects in the human body.

Physicists evaluate a specific imaging procedure by imaging the phantom and then analyzing the image to determine which objects are visible. This is a test of both contrast sensitivity and blurring. With reduced contrast sensitivity the objects with lower contrast will not be visible. Blurring reduces the visibility of the smaller objects.

A Contrast Detail phantom can also be used to evaluate the effect of noise on visibility as illustrated ion Figure 29.

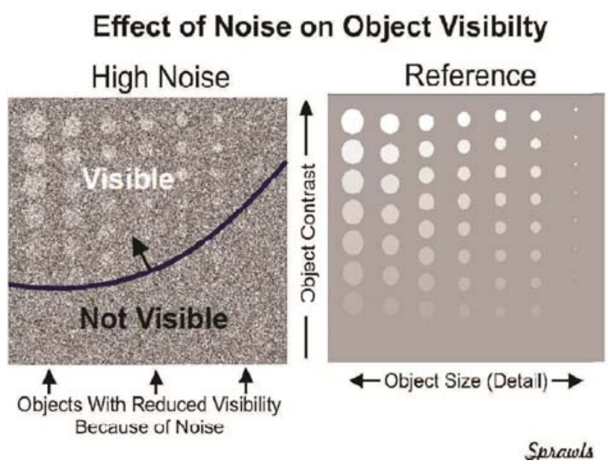


Figure 29. Using a Contrast Detail phantom to evaluate the effect of noise on the visibility of objects.

Testing an imaging procedure with a Contrast Detail phantom evaluates the effect of all three factors--contrast sensitivity, blurring, and noise--on visibility. However, it cannot determine the individual contribution of each of the factors to reduced visibility. Also, it does not provide one numerical value or score to represent the quality of an image.

Physicists measure the effect of blurring in an imaging procedure with the test device shown in Figure 30.

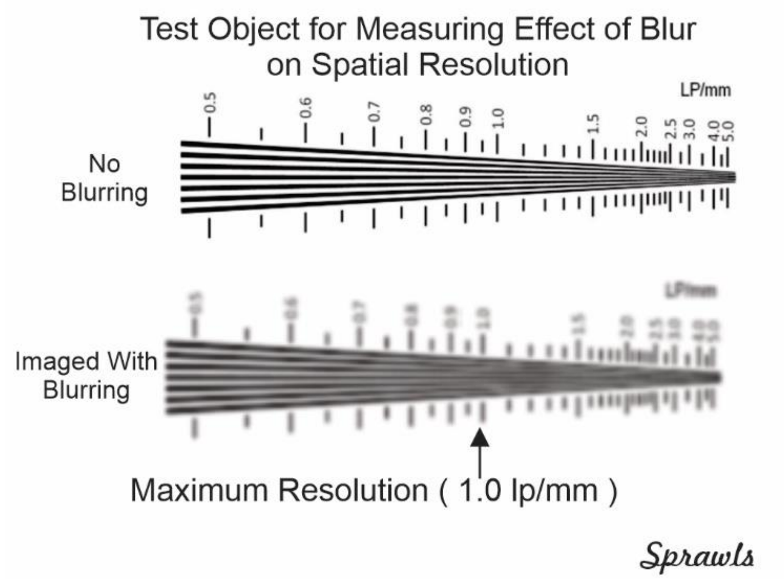


Figure 30. A test device with varying spatial resolution (size and distance between opaque lines) expressed in line pairs (a line and a space) per millimeter (mm) of distance.

Blurring reduces the visibility of the separation or resolution of the lines as shown. The highest spatial frequency that can be viewed as separated or resolved lines is the maximum resolution that provides a numerical value for the test.

Mammography is a procedure that is tested frequently by physicists to ensure that the image quality is adequate for detecting and diagnosing cancers. The specific test phantom for this is shown in Figure 31.

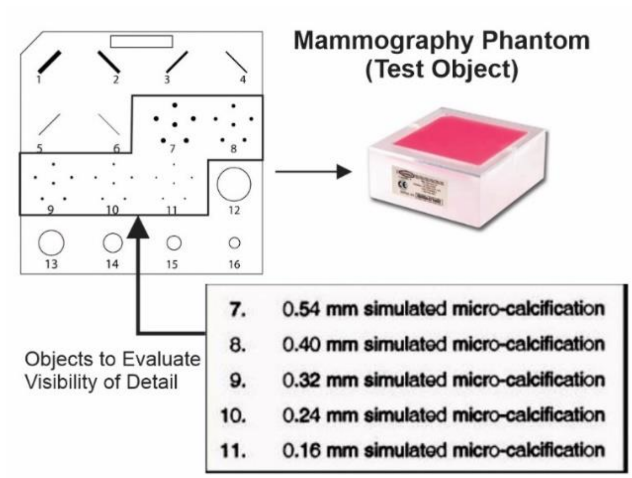
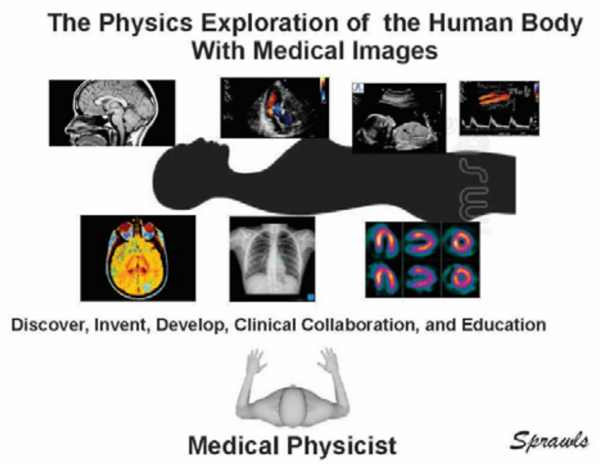


Figure 31. A test phantom specific for mammography that is used by physicists to periodically evaluate the performance of mammography system.

The phantom contains a series of objects varying in size and physical contrast, simulating objects and structures within a breast. A test is performed by producing an image and determining which objects are visible. This is a test that is required in many countries.

There are phantoms designed for the specific modalities, MRI, CT, etc., that are used by physicists in one of their major activities, ensuring the diagnostic quality of medical imaging procedures.

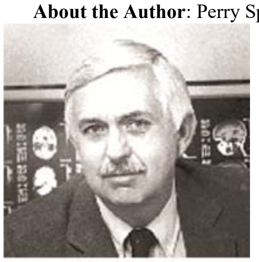
XII. THE MEDICAL PHYSICIST AND MEDICAL IMAGING



The human body is a complex physical universe that is, except for the skin surface, out of view with normal human vision. The ability to examine the interior of the body is critical to providing medical care, especially the detection and diagnosis of many major diseases and injuries. Before the 1880s the only significant access to the interior of the body for medical purposes was with surgery…cutting into the body. Then, in 1885 a major evolution in medicine occurred when the physicist, Wilhelm Roentgen discovered, researched, and demonstrated the use of a "new kind of ray", x-radiation, to produce images of the interior of the human body. This can be considered as the origin of the *medical physics profession* as we know it today. Medical imaging is a branch of physics involving the physical interactions of radiation and energy with the physical structures of the human body to produce images. Over the years many physicists along with other professionals have continued the development and evolution of medical imaging to expand its value within the practice of modern medicine.

In addition to research and development activities medical physicists are highly respected professionals working in collaboration with physicians, especially radiologists, in providing effective and safe imaging procedures and as educators.

About the Author: Perry Sprawls is a clinical medical physicist specializing in diagnostic radiology and medical physics education. He is Distinguished Emeritus Professor at Emory University School of Medicine in Atlanta and now contributes to medical physics education around the world through the Sprawls Educational Foundation, www.sprawls.org. It is the combination of his experience as a clinical physicist and educator that is the foundation for developing and sharing resources to support the teaching of medical physics. His continuing research and development activities are resulting in models for increasing the effectiveness of both the learning and teaching process, especially for clinically applied medical physics.



Dr. Perry Sprawls

Contact Information: sprawls@emory.edu .