Understanding and Optimizing Visibility in Medical Imaging Procedures

Image Characteristics and Controlling Factors

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Comparing medical imaging procedures to flying modern aircraft. Both require highly educated and experienced professionals.

This comparison emphasizes the complexity of modern medical imaging methods and the requirement for highly educated and experienced radiologists to guide the procedures to obtain the necessary visualization to detect, diagnose, and guide the treatment of diseases and conditions in the human body.

Provided here is an introduction to the characteristics of medical images that affect clinical visibility and how they can be controlled by a radiologist to optimize imaging procedures.

Introduction and Overview

While radiologists might not always touch the equipment and adjust the controls radiologists doe have the responsibility of selecting imaging modalities and methods and optimizing protocols for specific clinical procedures. Until a more detailed knowledge of equipment and the physics of image acquisition is acquired, our initial approach is primarily functional, focusing on the factors selected and controlled by the radiologist. At this time an imaging system can be considered as a "black box" with controls as illustrated in Figure 2.

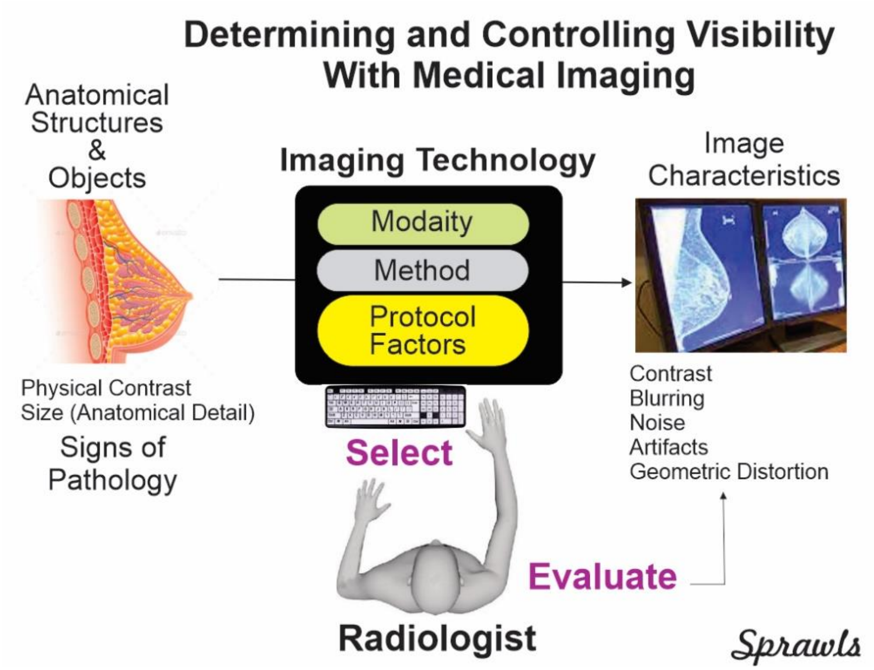

Figure 2. The factors that can be selected and controlled by a radiologist to obtain appropriate visibility in medical images.

This process requires knowledge of the *characteristics of images* that affect visibility in relationship to the characteristics of the structures, objects, and conditions within the body that are to be imaged along with the *imaging procedure factors* that determine or control the image.

Clinical Visibility

Medical imaging methods can be considered an extension and enhancement of a radiologist's vision as illustrated in Figure 3.

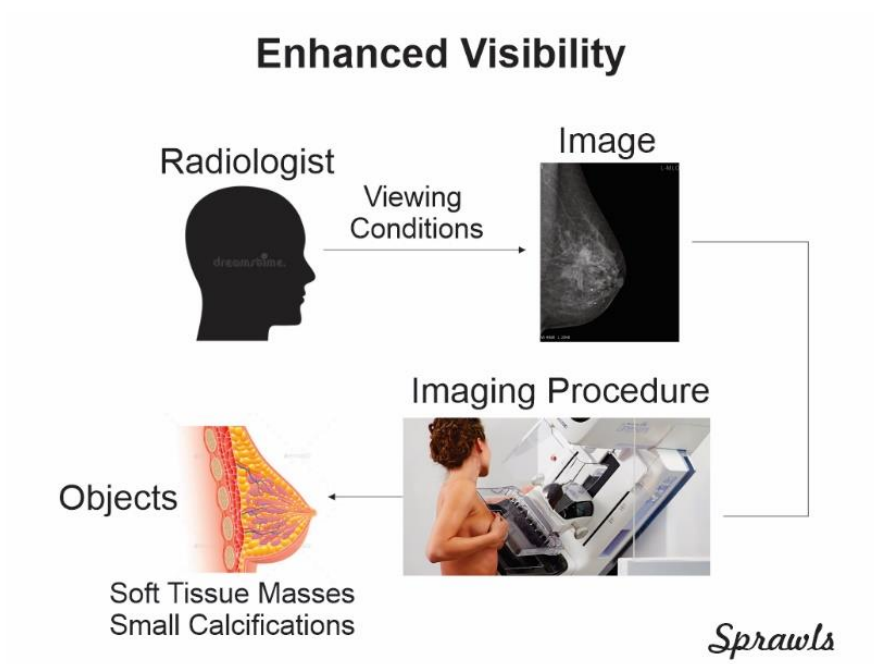

Figure 3. Medical imaging procedures enhance and extend human vision to see into a patient’s body and visualize pathological conditions--in principle comparable to a pathologist’s microscope.

Human vision has certain characteristics and limitations that are to be considered in relation to visibility. Two of these characteristics can be evaluated with the test charts/objects in Figure 4.

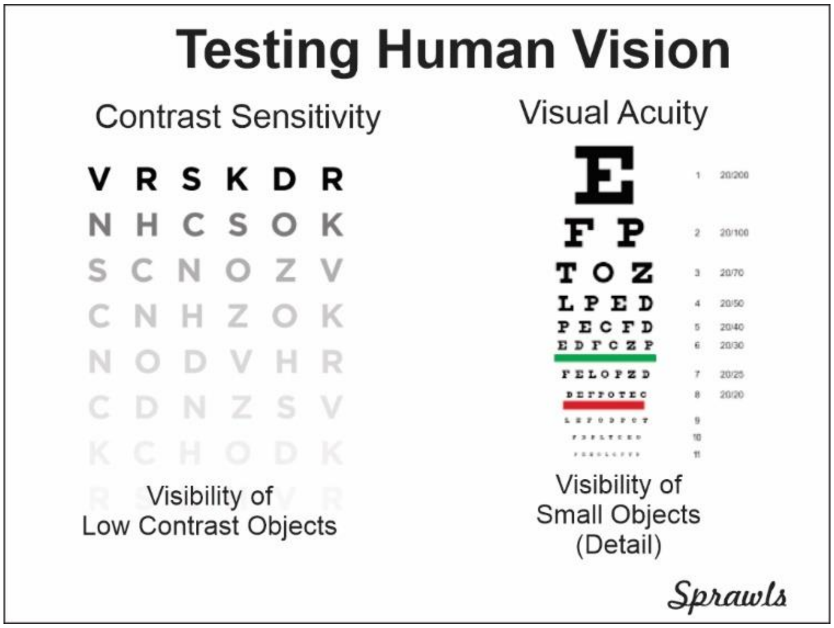

Figure 4. Two characteristics that limit visibility of objects in relation to their contrast and size.

Contrast sensitivity is the characteristic that relates visibility to the contrast of the objects being observed--letters of the alphabet in the test chart. Visual acuity relates to ability to see small objects or detail. It is limited by blurring within the eye.   These are two characteristics of human vision that extend to the medical imaging procedures.

Image Characteristics That Affect Visibility

There are five (5) specific image characteristics that have some effect on visibility. In addition to contrast sensitivity and blurring there are visual noise, artifacts, and geometric distortion. The three (contrast sensitivity, blurring, visual noise), referred to here as “the critical three”, are highly significant because they apply to all images. Artifacts and distortion are generally undesirable features but with less of a direct effect on visibility as the others.

A major issue is that the critical three often have opposing or conflicting effects on visibility and on other factors including radiation exposure to patients and image acquisition time, depending on the modality. Because of this interactivity the protocol for a specific clinical procedure should be optimized under the direction of a radiologist who can evaluate image quality and characteristics in relation to features in the body that are to be visualized and then adjust protocols as needed.

Radiologists need a knowledge and understanding of the characteristics of images in relation to the characteristics of the objects or conditions in the body that are to be visualized. This then enables the overall control of the imaging procedure to obtain the required visibility.

The necessary visibility is achieved by selecting an appropriate imaging *modality* and *method* and then selecting the combination of imaging *protocol factors*, also known as technique factors. For most clinical requirements the modality and methods are established from experience and available in publications including the ACR Appropriate Criteria.

For an individual imaging procedure, it is the selectable and adjustable protocol or technique factors that must be considered to optimize visibility. These are the factors that establish the relationship between image characteristics and the physical characteristics of objects within the body as illustrated in Figure 5.

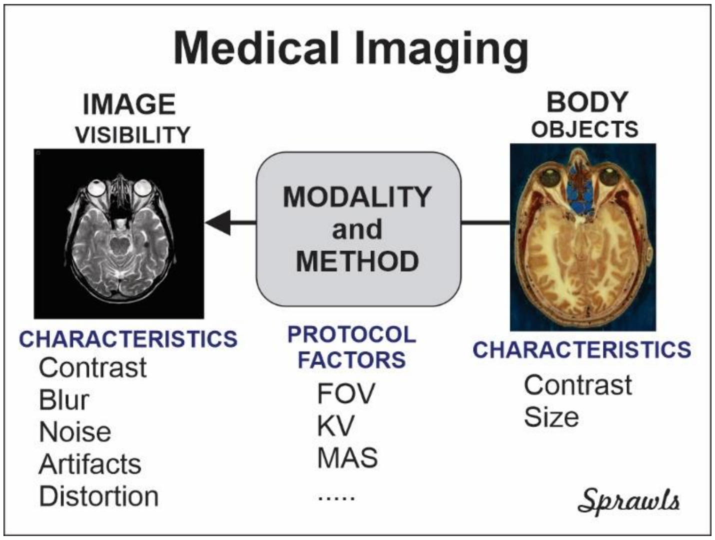

Figure 5. For a specific modality and method, for example CT and with spiral acquisition the protocol factors can be used to adjust the image characteristics for visualizing objects in the body in relation to their characteristics.

Object and Image Contrast and Procedure Contrast Sensitivity

The general meaning of the word *contrast* is the difference between or among things. It is the fundamental and major characteristic of images. Within an image, objects are visible because they have contrast and are different with respect to the surrounding area in either brightness or color. A certain level or amount of contrast is required for objects to be visible depending on viewing conditions (image brightness and room illumination), the visual acuity of the person, and the size of the object being viewed.

Objects in a body have *physical contrast* and objects in an image have *visible contrast*. The characteristic of an imaging procedure that relates contrast of objects to image contrast is *contrast sensitivity*.

Image Contrast

The *overall contrast* of an image is the range of brightness levels (or film densities) throughout the image as illustrated in Figure 6.

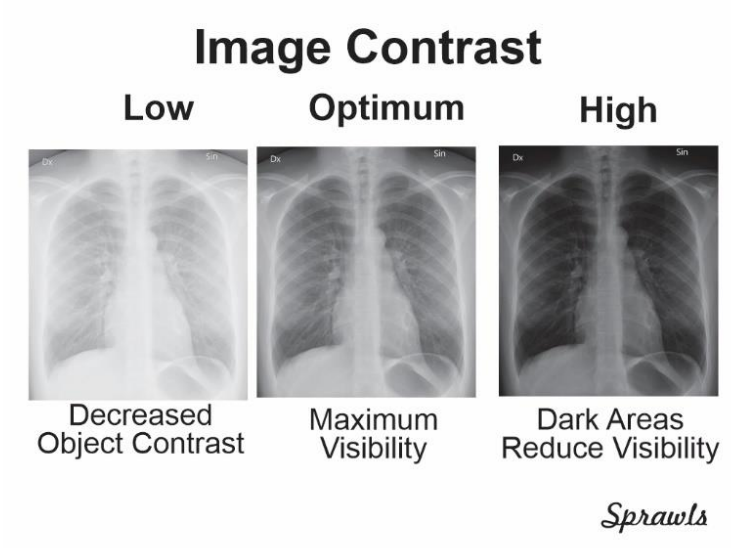

Figure 6. Different levels of image contrast and effects on visibility.

While contrast is a requirement for visibility of specific objects or structures, high overall image contrast is not always a desirable feature, as illustrated in Figure 6. In images with high overall contrast there can be areas that are either very light or dark in which the contrast and visibility of objects and structures is diminished.

Images with undesirable high contrast can result from imaging anatomical regions with a large range of either density, as in the chest, or thickness, as in the breast. The dark areas can reduce visualization by the observer. In the days of film, the contrast was reduced or completely absent in the dark areas.

This was an especially significant problem with images recorded on film. After an image is recorded on film the contrast cannot be changed or adjusted. A great advantage of images in a digital form is that the contrast of the displayed image can be adjusted by a radiologist. The window controls can be used to enhance visibility in the different anatomical regions as illustrated in Figure 7.

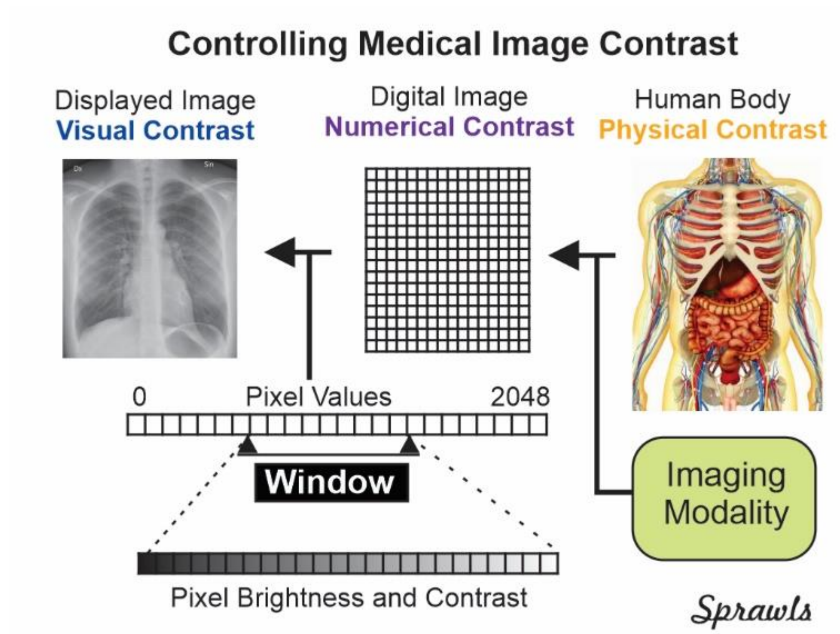

Figure 7. Controlling and optimizing contrast and visibility in a displayed image by setting the window center position and width on the pixel value scale.

A displayed image viewed by a radiologist is produced in two phases. The first being the production of a digital image by the imaging system. Each of the imaging modalities, CT, MRI, etc. produces a digital image from the physical contrast in the body. This is through a variety of physical interactions and mathematical computations that produces a numerical value for each pixel in the image that relates to physical characteristics of the corresponding tissue area in the body.

Physical Contrast Within the Body

The physical characteristics of tissue that determines pixel values and image contrast for several of the imaging modalities are identified in Figure 8.

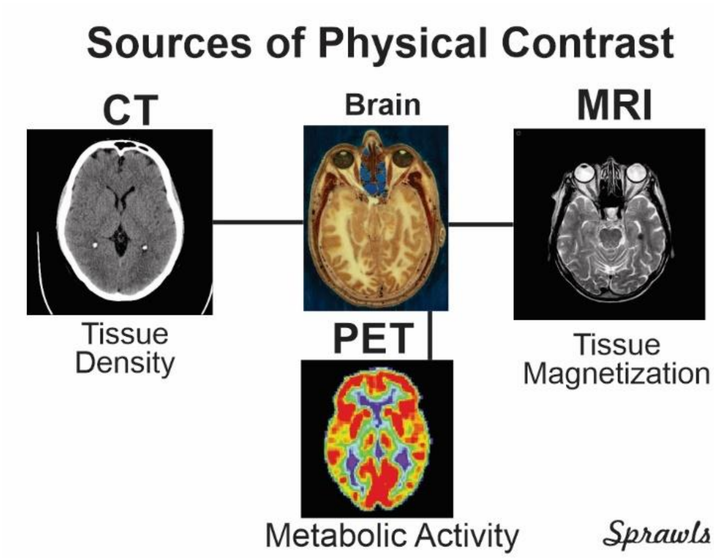

Figure 8. The types of physical contrast among tissues that form visible contrast in displayed images.

Medical imaging is a physical process. The unique feature of each of the imaging modalities is the physical characteristics of tissues that are transformed into visible images. It is when these physical characteristics are different for pathologic and normal tissues that makes the detection and diagnosis of many diseases possible.

Object Contrast

In general, it is not the overall contrast of an image that is the significant factor. It is the contrast of individual objects or anatomical structures within the image that determines diagnostic value. For an object within a body to be visible in an image it must have some form of physical contrast as described above with respect to the surrounding area.

The visibility of a specific object, micro-calcifications in a breast for example, depends on two characteristics: contrast and size.

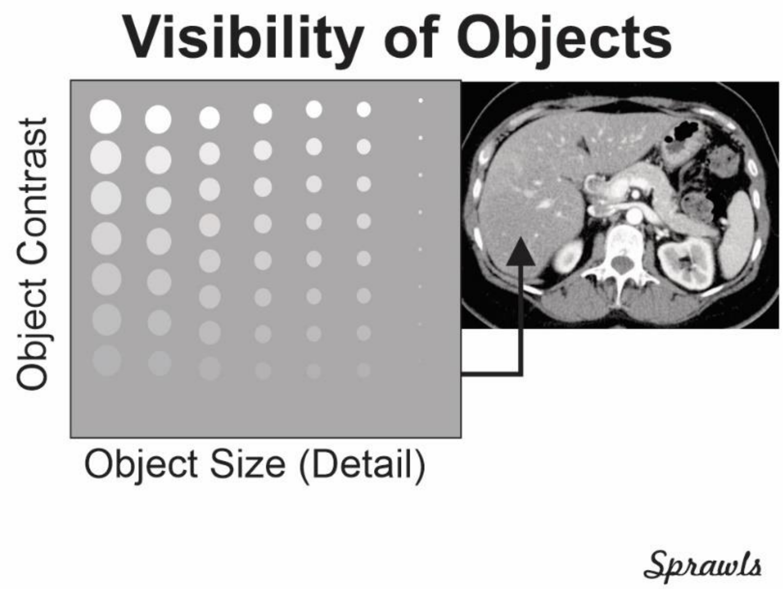

Figure 9. For a specific observer and viewing conditions the visibility of objects depends on their size and contrast. That is illustrated here with a Contrast – Detail Chart with objects arranged by contrast and size simulating objects within the human body.

As we can observe the large objects with high contrast are easy to see. Visibility decreases as the object contrast and size are decreased.

Procedure Contrast Sensitivity

Contrast Sensitivity is the characteristic of an *imaging process* that determines the lowest contrast objects that are visible. It is the ability of an imaging process to convert and transfer the *physical contrast* within the body to the *visible contrast* displayed in an image as illustrated in Figure 10.

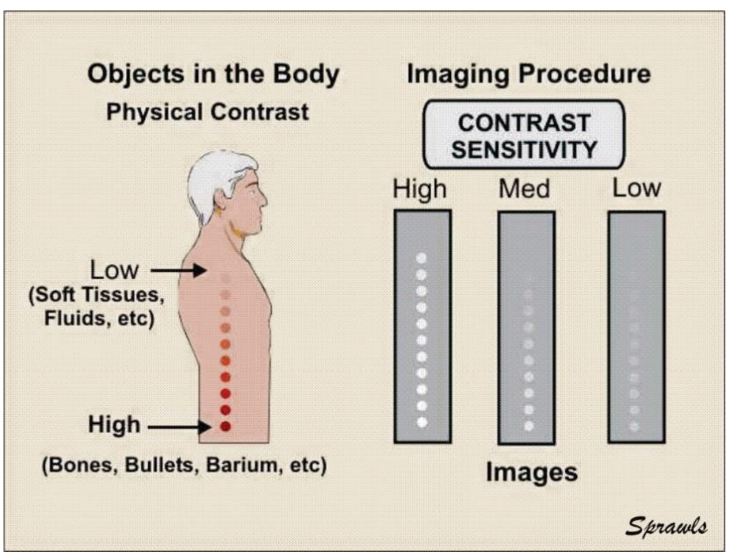

Figure 10. The concept of Contrast Sensitivity.

Contrast Sensitivity is a predominant characteristic of each of the medical imaging modalities (Radiography, CT, MRI, etc.) that determines their clinical applications. In an imaging procedure there is no one factor that determines and controls Contrast Sensitivity. It is determined by a series of factors beginning with how images are formed with the various modalities, selected protocol factors, image viewing conditions and adjustments, and the visual abilities of the radiologist.

A major objective in the development of new and improved imaging modalities and methods--mammography is an example--is increased Contrast Sensitivity so that more pathological conditions are visible.

Blurring and Visibility of Detail

Every imaging process, including human vision, is affected by some amount of blurring that limits the visibility of detail or small objects. For human vision this is most often described as visual acuity and is tested with charts as illustrated in Figure 4. This reduced visibility of small objects, such as letters of the alphabet, results from blurring within the eye, especially the reduced ability to focus the lens of the eye relating to ageing.

Some blurring occurs in all medical imaging procedures and is a factor that must be considered when selecting methods and adjusting protocol factors for specific clinical procedures.

It is the blurring that limits visibility of objects and structures because of their size, or visibility of detail as illustrated in Figure 11.

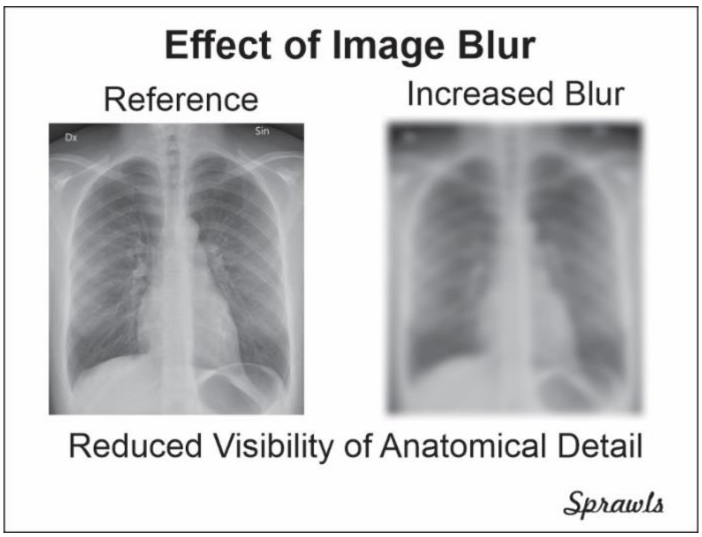

Figure 11. The effect of blurring on the visibility of detail within a clinical image.

The blur shown here is very large compared to what would be in an actual clinical image and is used to help illustrate the effect on visibility of small structures and objects.

The Blurring Process and Effect

Blurring occurs in all imaging procedures because of the physical characteristics of the various elements or components of the imaging system. Although the causes of blurring among the imaging modalities are very different, the basic process is ilustrated in Figure 12.

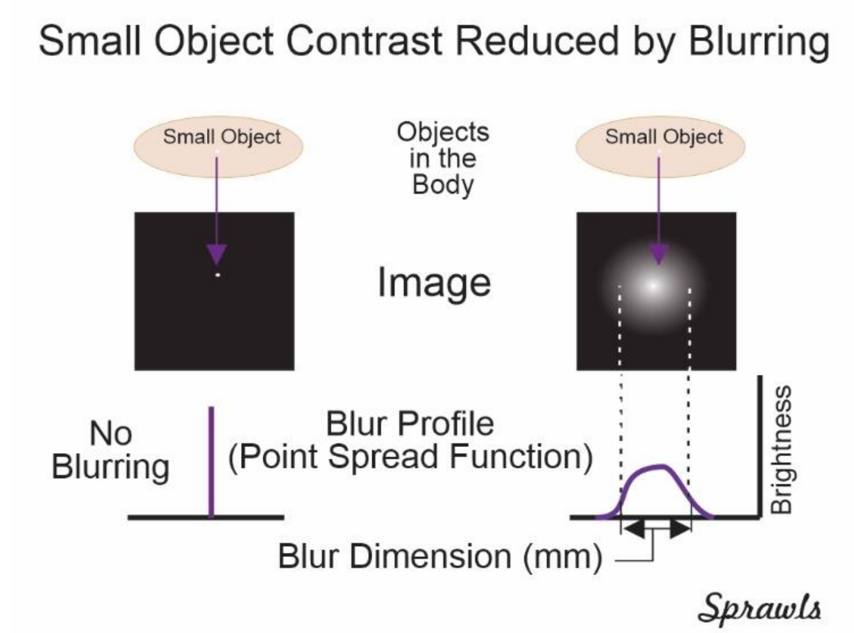

Figure 12. The effect of blurring on visibility of a small object.

If a small object in a body is imaged with no blurring (which is not possible) the image would be a small bright and highly visible point in the image as illustrated. The effect of blurring is to spread or smear the brightness over a larger area which reduces its contrast and visibility. As the blurring is increased the brightness and visibility continues to decrease and the object becomes invisible. The loss of visibility depends on the relationship between the size or dimension of the blur and the size of the object. For medical imaging methods blur values range from approximately 0.1mm for mammography to several mm for the radionuclide imaging methods.

Author's Observation: The smallest anatomical object that will be visible is often about the same size as the blur in the procedure.

That is not an established physical fact but provides some understanding of the significance of blurring in medical imaging.

Figure 12 compares an image blur with no blur with a profile of the brightness in an image. The profile has a scientific name--point spread function (PSF). The dimension of a blur in medical imaging is very small, especially in mammography and general radiography, making it difficult to measure directly. Therefore, other methods are used to evaluate are used to evaluate blurring in clinical practice.

Measuring and Evaluating Blur in Clinical Imaging

Blurring is a major and often limiting factor in medical imaging and needs to be determined and evaluated at several levels. These include the selection of imaging equipment, evaluation of equipment performance or quality control programs, and optimizing imaging procedure protocols for specific clinical examinations The dimension of a blur in medical imaging is very small, especially in mammography and general radiography, making it difficult to measure directly. Therefore, other methods are used to evaluate. The two most often used methods are observing visibility of detail (objects of varying sizes) and limitations on a characteristic known as spatial resolution, described later. Each method is conducted by imaging test objects, often referred to as phantoms, and then evaluating the images.

Measuring Visibility of Detail

In the clinical setting test devices or phantoms with object sizes comparable to the anatomical or pathological objects of interest and the blur values for that modality are used. The test phantom used in mammography is illustrated in Figure 13.

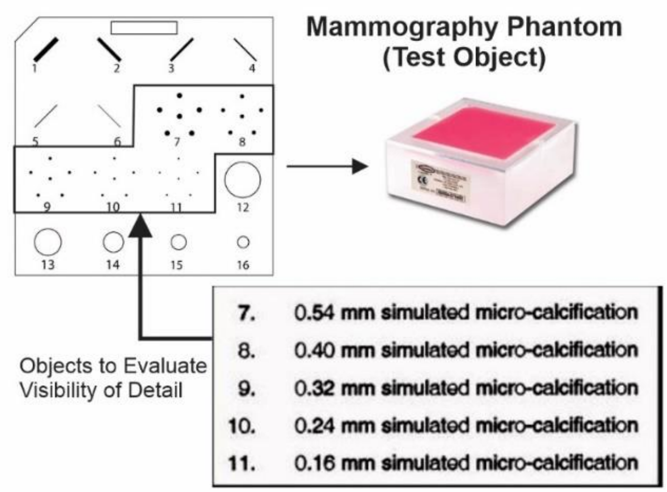

Figure 13. The phantom/test object used for the routine and often required evaluation of mammography image quality.

Small micro-calcifications are valuable signs of breast cancer, and their visibility is a critical feature in mammograms, the one with the least blurring *tolerance*.

Visibility is limited both by the contrast sensitivity and blurring of the imaging process. It is the effect of blurring and visibility of detail that is considered here. The phantom contains several groups of objects to test different characteristics of image quality. One group consists of small, simulated calcifications of varying sizes to evaluate visibility of detail as limited by the blurring. As shown, these range in size from 0.16 mm to 0.54 mm. The score is the number of groups in which the objects are visible. For some accreditation requirements, visibility of three groups, including the 0.32 mm calcifications, was required. This demonstrates that of all imaging modalities, mammography is the one with the least blurring and greatest visibility of detail.

Phantoms for the other modalities contain objects with sizes comparable to the characteristic blurring for that modality.

Spatial Resolution

Spatial resolution is a characteristic of an imaging process and the resulting image that is affected by the blurring. It can be measured and is often used to evaluate the effect of blurring. While spatial resolution does not apply directly to clinical images, where visibility of detail is the significant and observable factor. It is often found in the literature, in descriptions of imaging systems, the selection of imaging equipment and is a common term used by radiologists. Spatial resolution is measured and used by physicists in evaluating imaging equipment as a quality control requirement.

One of the several meanings of “resolution” is the ability to see the difference or separation between objects as illustrated in Figure 14.

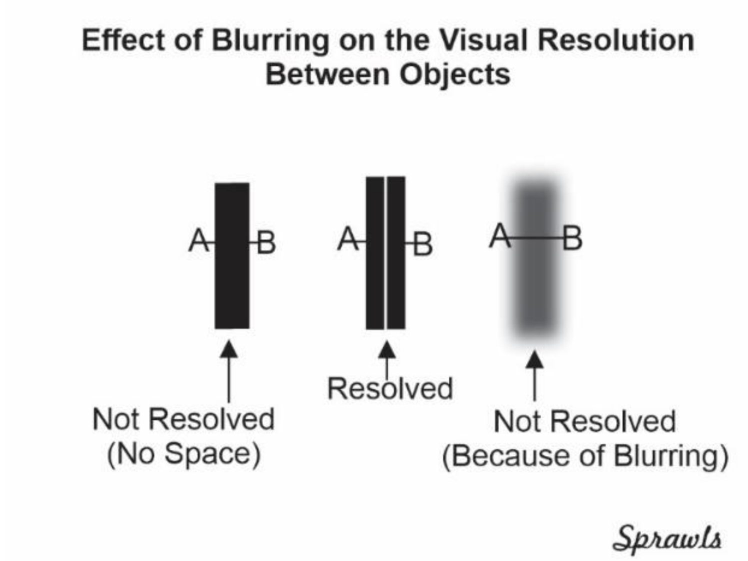

Figure 14. The concept of spatial resolution and the effect of blurring.

Two objects (lines) are used to illustrate the effect of blurring on the visual resolution between objects in an image. Resolution is the ability to see a separation between objects. It can be limited by no space between objects or by blurring. When objects are *blurred together* in an image they cannot be seen as separate objects or resolved. This is an effect that can be easily seen in images of test devices or phantoms containing line objects with varying separation distances as illustrated in Figure 15.

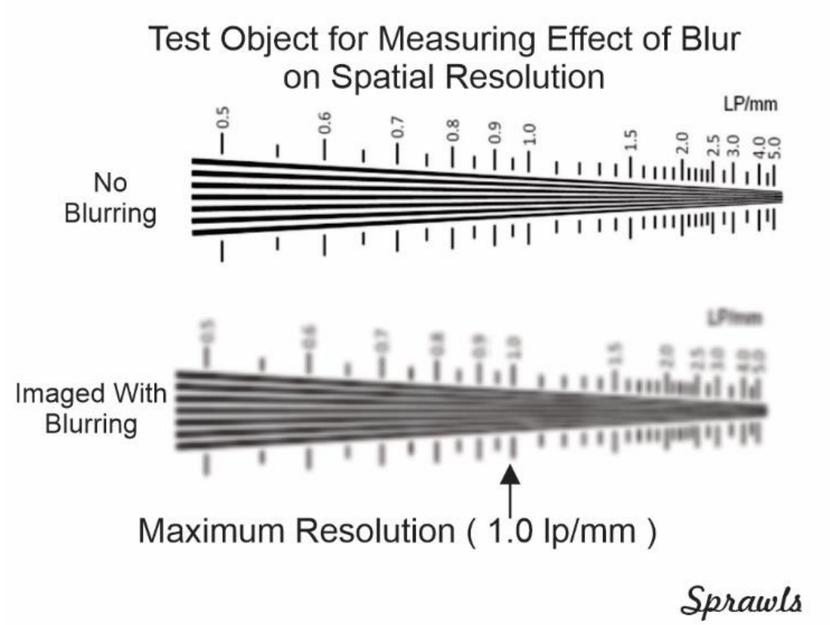

Figure 15. A test object used to measure resolution as affected by blurring.

Test objects used to measure resolution capability and the imaging process consist of line objects separated by spaces. A line and the adjacent space form a line pair (LP) and the size is specified as the number of line pairs in a unit of length, LP/mm is shown in Figure 15. This is the quantity of *spatial frequency* that can be used to describe the performance of an imaging process with respect to blurring. Small objects are associated with high spatial frequencies, LP/mm. In the spatial frequency domain, blurring reduces visibility of the high frequencies (small objects). As blurring is increased the maximum frequency (LP/mm) that is visible is reduced. For the blurred image in Figure 11 this is 1.0 LP/mm.

The maximum frequency at which there is visibility (1.0 LP/mm) does not completely describe the effect of blurring. Blurring reduces the visible contrast of the lower frequency and larger objects progressively up to the point of invisibility as illustrated in Figure 16.

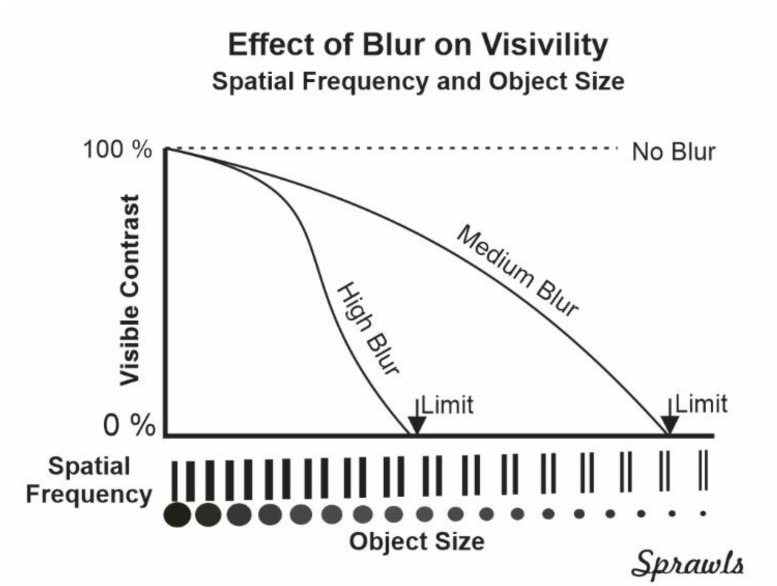

Figure 16. Measuring the effect of image blurring in the spatial frequency domain,

We don't have line pairs in the body but we do have small anatomical structures, like calcifications, that we need to see. So why are spatial frequency and line pairs used to measure the effects of blurring in medical images? The reason is ease of testing. With an appropriate test object, like that shown in Figure 15, an image can be created which shows which line pairs are resolved. This method is used with quality control procedures and evaluating equipment performance for accreditation and regulatory requirements which have required limits.The modulation transfer function (MTF) is another characteristic of medical imaging systems used to express the effect of blur in the spatial frequency domain in the units of cycles/mm. It is similar in principle to the graph shown in Figure 16. It is not used to evaluate blurring in quality control procedures in clinics but in research laboratories and sometimes to describe commercial products for medical imaging.

Blurring With the Imaging Modalities and Methods

Some blurring is inherent in *every imaging procedure* related to how the images are created. This is generally related to the design limitations of the technology which have advanced over the years for improved image quality.

The blurring and visibility of detail characteristic of each imaging method is a significant factor in determining the clinical procedures that the method can be used for. This is generally determined by the smallest objects or structures that must be visible in an image for diagnostic or therapeutic purposes. This can range from micro-calcifications in mammography to relatively large areas of radioactivity in the radionuclide imaging methods.

Figure 17. provides an overview of the modalities with respect to image blurring and visibility of detail.

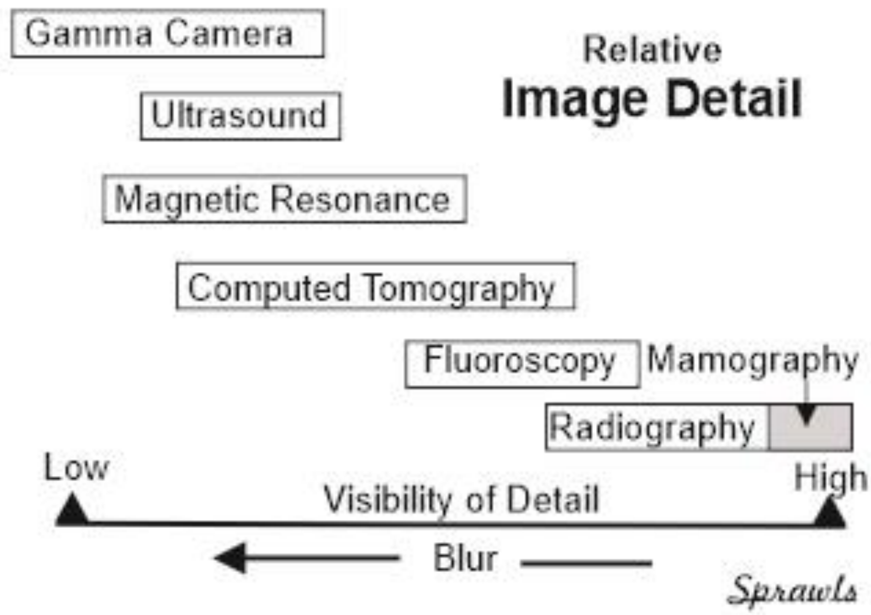

Figure 17. The relative blurring and visibility of detail for the imaging modalities.

For each imaging modality there is a range of blur values and visibility of detail as shown. Some of these are related to the design of the equipment and ongoing developments over the years. However, the highly significant factors that must be considered for specific clinical procedures are the adjustable protocol or technique factors that affect blur that must be selected.

With each of the medical imaging methods there are several sources of blurring as illustrated for one in Figure 18.

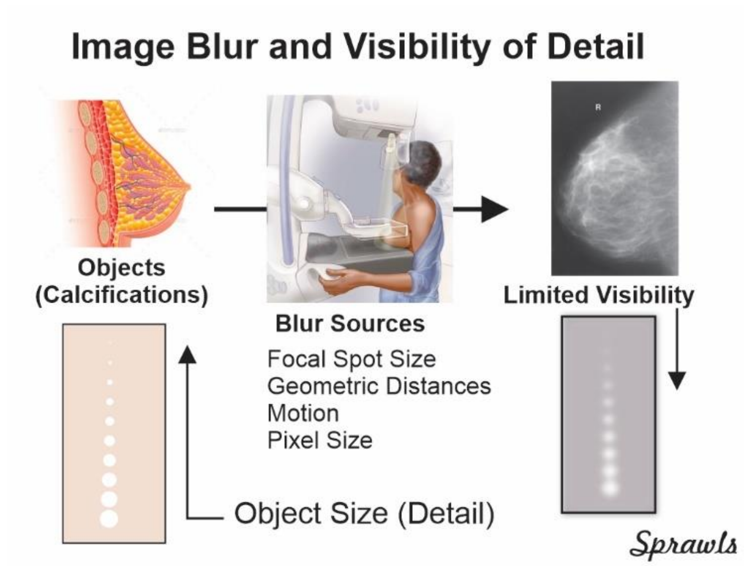

Figure 18. The visibility of small objects within the body limited by blurring that occurs during the imaging procedure.

Mammography is used as an example here, but the principle applies to all medical imaging procedures. With each modality there are several physical conditions in the image forming process that produce and control the blur in the image. Some of these can be adjusted for a specific clinical procedure. For mammography these include focal spot size, geometric distances, and image formats as described later.

Why Not Minimum Blur and Maximum Visibility of Detail?

If the blurring is generally adjustable as described here, why not go for the best visibility of detail in all procedures? This is a major factor that must be considered in setting up the protocol or technique for each clinical procedure. The need for visibility of detail must be balanced or optimized with other requirements including controlling radiation dose and visual noise as described later.

Digital Image Structure and Blurring

The structure of the *digital image* used in the modalities is a major factor affecting three of the image characteristics--blur, visual noise, and contrast. Several of the factors relating to the structure of a digital image are variable, either by the design of the equipment or adjustable protocol factors and are illustrated in Figure 19.

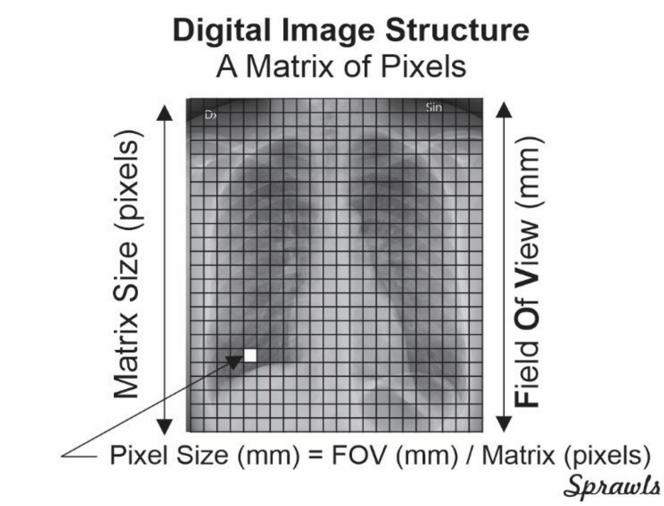

Figure 19. Image pixel size determined by the ratio of field of view (FOV) to matrix size.

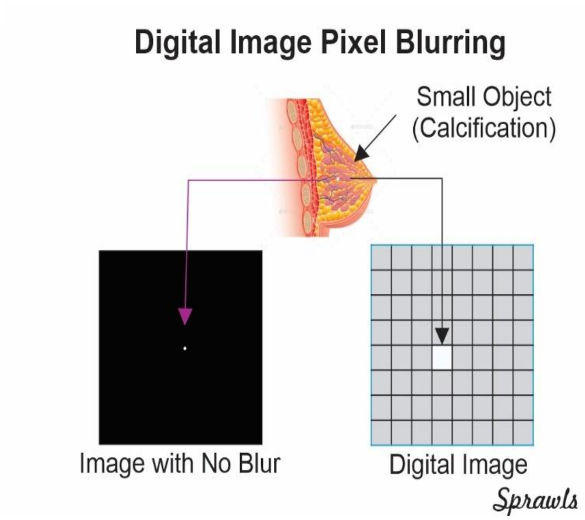

Figure 20. Blurring produced by pixel size.

A digital image is a matrix of pixels (picture elements) in which the size of the pixel is a major factor in determining both *visibility of detail* and *visual noise*, to be discussed later. As shown, pixel size is the ratio of the FOV to the matrix size in each direction. In some modalities, especially radiography, matrix size is an equipment design characteristic and not changeable by the clinical staff. With other modalities including CT, and MRI there are design limits, but it is one of the adjustable protocol factors in setting up a procedure. Our interest currently is on the effects of pixel size on blurring and visibility of detail.

A Pixel is a Blur

In every imaging method that produces images in a digital format an additional source of blurring is added. The significance generally is the relationship of the digital pixel blurring to the blurring by other factors in the imaging process such as x-ray focal spot sizes, CT detectors, etc. The blurring effect of digitizing an image is illustrated in Figure 20.

The pixel is the smallest area than can be displayed in a digitized image. The image of a small object is spread out or blurred to the size of the pixel. Adjusting pixel size by selecting FOV and Matrix values for an imaging procedure is used to control the blurring and visibility of detail.

Tomographic Imaging and 3D Blurring

With the tomographic imaging modalities (CT, MRI, SPECT, etc.) there is an added blur dimension, the thickness of the slice. In the imaging process the slice of tissue is divided into voxels as illustrated in Figure 21.

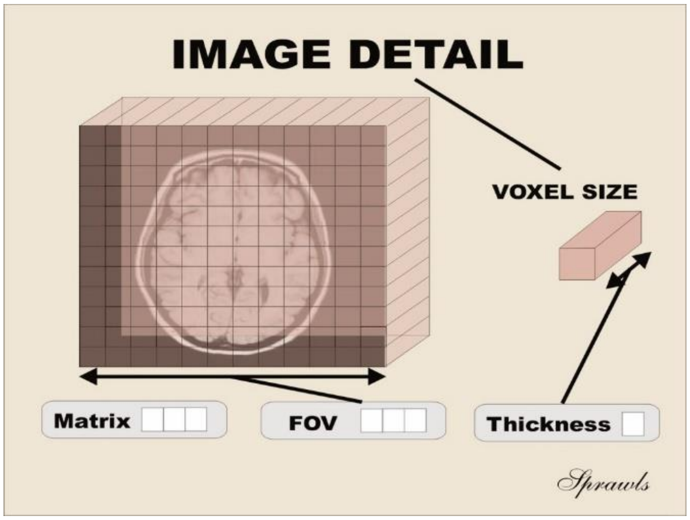

Figure 21. Voxel size is one of the sources of blurring and can be controlled with the combination of three protocol factors.

Composite Blur in Medical Imaging Procedures

In each of the imaging modalities there are multiple sources of blur relating to the process for producing images. These are generally related to the design of the equipment for a specific modality and that establishes the range and limits of blurring and visibility of detail as illustrated in Figure 17. The total blur in an image is a composite of the individual blur sources. It is not a direct mathematical addition but a more complex blending relationship that will not be covered here. Each source of blur contributes to the total image blur, but the larger sources generally predominate.

This is significant because each section of the human body is being viewed through a series of blurring processes. Many of the sources of blurring are adjustable when setting up the protocol for each imaging procedure as illustrated in Figure 22.

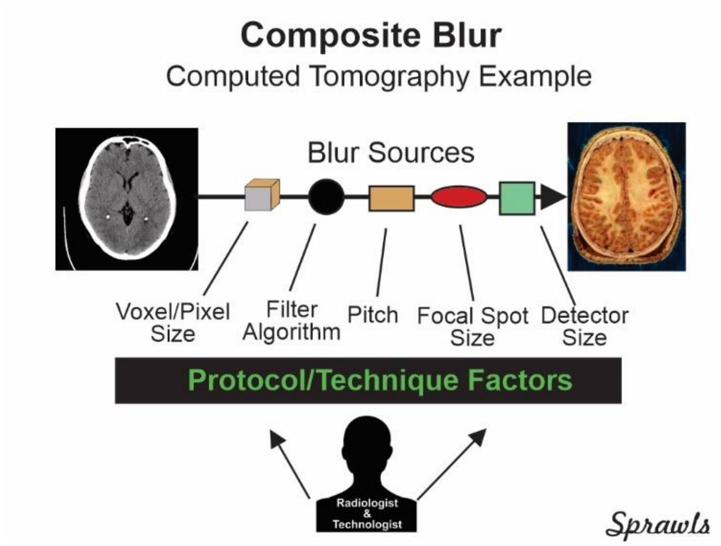

Figure 22. The composite of multiple sources of blur that can be adjusted by the imaging staff.

Summary and Overview of Image Blurring

Medical imaging facilities have established protocols for each type of procedure. These are generally specified by a radiologist and set up and adjusted on the equipment by a technologist for each patient examination. With knowledge of each of the blur sources the staff will have a better understanding of each protocol and how to adjust as needed.

While there might be a desire to change some of the factors to reduce blurring there are often tradeoffs to consider. Changing a factor to reduce blurring can have an undesirable effect of increasing some other characteristic such as image acquisition time, x-ray tube heating, and especially visual noise as will be discussed later. Especially when there are tradeoffs, there is limited value in reducing one of the factors much below the combined value of the others.

An optimized imaging protocol for a specific procedure is one in which the factors are balanced with respect to the tradeoffs and in relation to each other.

Figure 23 provides an overview of the factors contributing to the blurring and limits on visibility in medical Images.

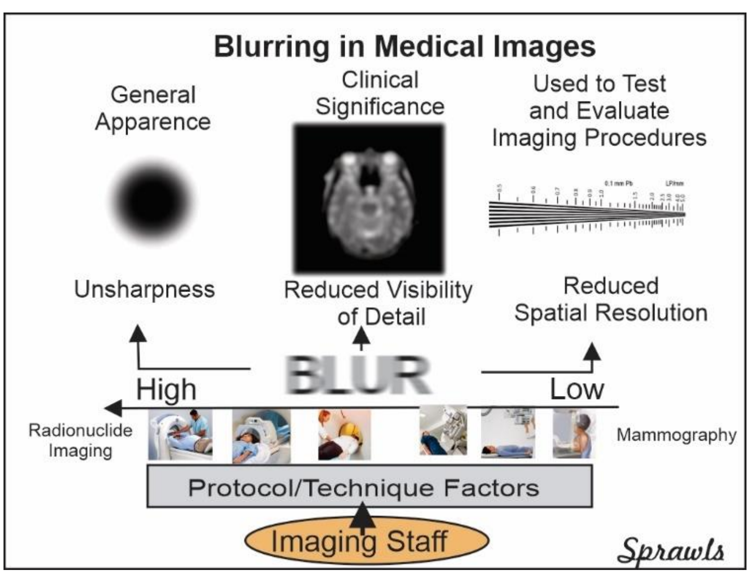

Figure 23. A summary and overview of blurring in medical images.

There is some blurring in all images that produces three observable effects. A common term is image un-sharpness. It can be measured with test objects in terms of spatial resolution. The clinical significance is the effect on anatomical detail or small objects of medical interest in the body. Blurring is produced during the formation of images with each of the medical imaging modalities and depends on the physical dimensions of components (focal spots, detectors, collimators, pixels, etc.). Blurring is a major characteristic of each modality and determines the types of clinical procedures that can be performed, generally relating to the smallest anatomical structures or objects within a body that must be visible.

With each modality there are several sources of blur, and some can be adjusted for specific procedures. It is the values of these factors that form the protocol for a specific procedure.

Visual Noise

Visual noise, like audio noise is generally an undesirable characteristic that interferes with and distracts from the intended content of the image or sound. In images it is a random variation in brightness or color that is super-imposed on or added to the image as illustrated in Figure 24.

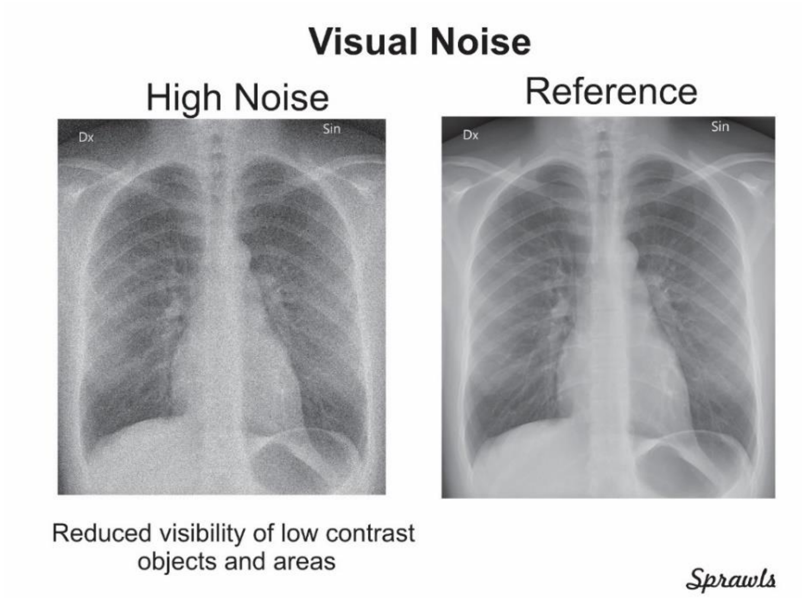

Figure 24. The general appearance of visual noise in a radiograph.

Some level or amount of noise is present in most images and especially medical images. It is a major characteristic that must be considered by radiologists in selecting imaging methods and protocols for specific procedures. It is usually adjustable and can be set for each procedure. This requires considerable knowledge of the source of noise, its relationship to visibility of anatomical structures and signs of pathology, and especially the compromises with other factors including radiation exposure to patients, image detail and time to acquire

The Effect of Noise on the Visibility of Objects

The effect of noise on the visibility of objects is illustrated in Figure 25.

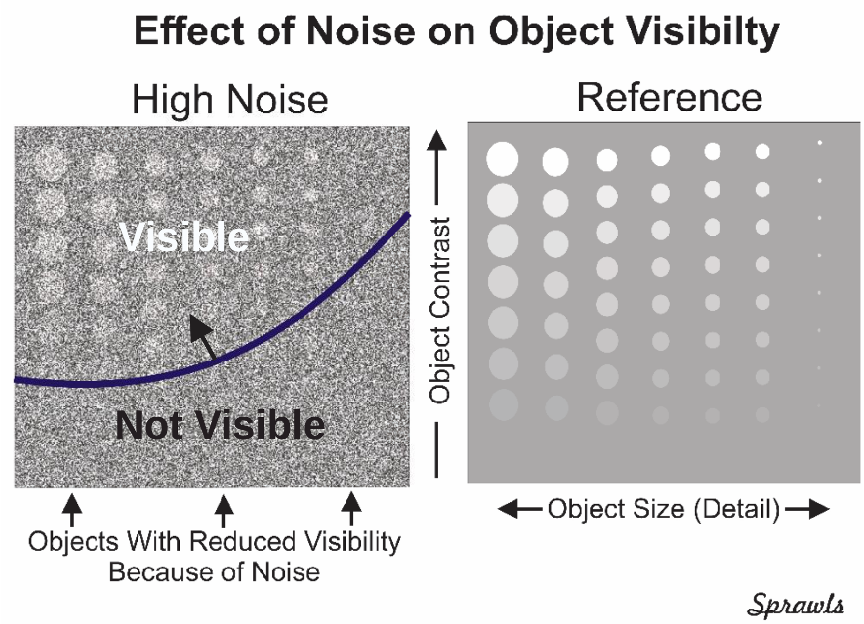

Figure 25. Visibility of objects reduced by noise relating to their characteristics. The amount of noise establishes a boundary between the visible and invisible.

As described previously, the two major characteristics of objects within the human body that affect their visibility are size (detail) and their contrast with respect to the surrounding area or background. These are the characteristics represented in a Contrast-Detail Diagram as shown in Figure 25.

A specific level of noise establishes a boundary between visible and invisible objects in relation to their contrast. This boundary moves with the level of noise. Noise reduces the visibility of objects in relation to contrast whereas blurring reduces visibility in relation to object size (detail). These are two very different effects that must be considered. In many cases, small objects such as micro-calcifications in the breast also have low contrast and their visibility is reduced by both noise and blurring.

The major source of noise depends on the imaging modality. For x-ray and radionuclide or nuclear medicine imaging it is the statistically random nature of radiation photon interactions. With MRI it is the random production of undesirable radio frequency (RF) radiation within the human body. Fortunately, these can be controlled and compensated for when setting up imaging procedures.

Visual Noise in Radiography and Mammography

In radiography and mammography, images are formed by projecting an x-ray beam through the body and producing shadows of the anatomical structures relating to their attenuation of the x-radiation. In this process two overlying images are formed. One is of the anatomy and the other is an image of the x-ray beam itself as illustrated in Figure 26.

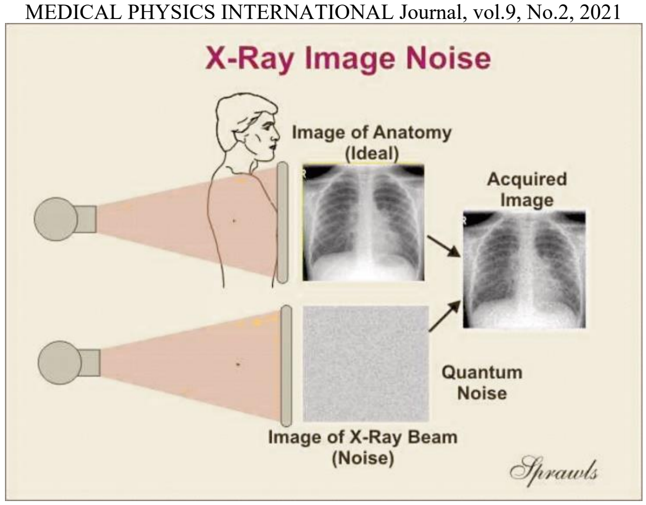

Figure 26. The image of the x-ray beam is the source of visual noise in radiographs.

An x-ay beam can be considered as a shower of many individual units of energy—photons--as illustrated in Figure 27.

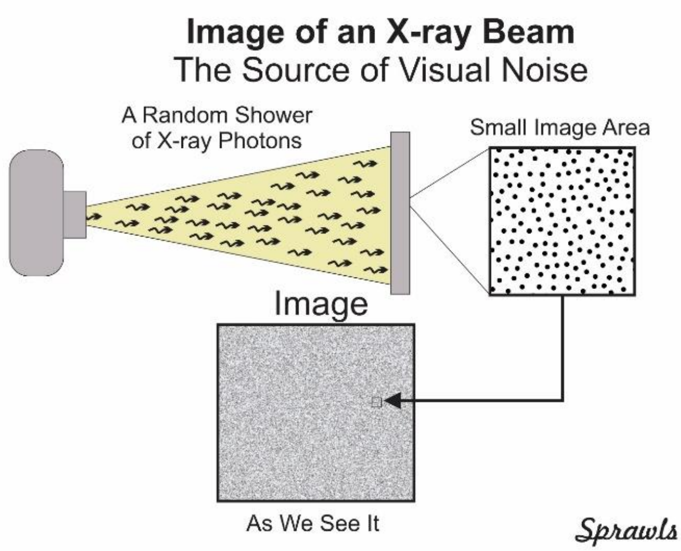

Figure 27. The random distribution of x-ray photons to the image receptor that appears in the image as visual noise.

X-radiation is a form of so-called electromagnetic radiation that is in the form of. small units or quanta of energy~~,~~ called photons. They have no mass, just energy, and move at the speed of light which is also in the electromatic spectrum. It is the energy in each individual photon that determines it type (x-ray, light, etc.) and how it interacts with matter like human tissue to form images.

The energy of photons is expressed in the units of electron-volts (eV). X-ray photos have energies of thousands of electron-volts (keV). An x-ray beam for general radiography generally contains photons with a spectrum of energies ranging from approximately 20 keV up to a maximum energy determined by the setting of the KV technique factor for each procedure. Mammography is performed with a spectrum with photons in the general range of 20 keV to 28 keV. The energy spectrum of the photons is a major factor in controlling image contrast in relationship to radiation exposure to patients.

The interest here is on the random nature of photon interactions as a source of image noise and how it can be controlled. Figure 28 illustrates how the natural variation in photon interactions produces visual noise in an image.

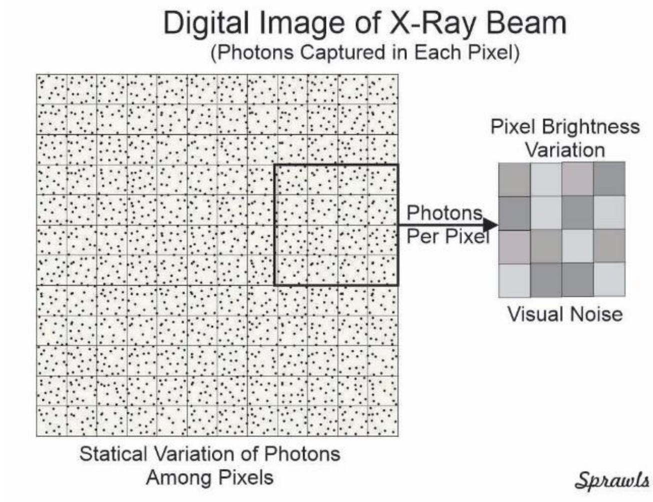

Figure 28. Visual noise in an image produced by the statistical variation in the number of x-ray photons captured in each pixel area of the image receptor.

The ability to adjust and control an imaging procedure and optimize for specific clinical cases is achieved by controlling the characteristics of the radiation, both x-ray and gamma, used to form the images. With respect to visual noise, it is the ability to control the random variation in the photons delivered to the imaging receptor.

Both the production and interaction of radiation photons are statistical events following established mathematical relationships. The *Poisson Distribution* is the relationship that connects image noise (the variation in photons per pixel) to factors that can be controlled to some extent in an imaging procedure. It is the statistical principle on which medical imaging with photons is based and fundamental to controlling and optimizing image quality and radiation exposure to patients as illustrated in Figure 29.

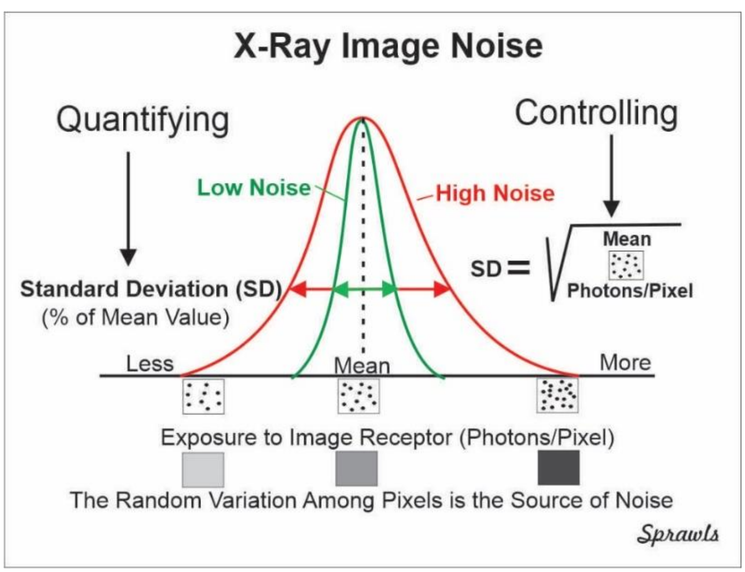

Figure 29. The random distribution of x-ray photons among pixels that is the source of visual noise.

In radiography, noise is the naturally occurring random variation in the number of x-ray photons among the pixels in an image. As illustrated in Figure 19 this follows an established statistical distribution. The so-called Standard Distribution (SD) is a characteristic of the distribution that can be used as a measure or quantification of the amount of noise. It is a factor that expresses the width or range of the distribution. Specifically, it is the range in which 68% of the pixel values fall. It is a measurement of the noise. The ability to control noise is through the relationship of the SD (the level of noise) to the number of x-ray photons per pixel captured in the image receptor.

It is the noise expressed as a percentage of the mean or average number of photons per pixel that is significant. Consider this example.

$$100 \text{ photons/pixel, SD} = \sqrt{100} = 10, \ 10\% \text{ Noise}$$

$$1000 \text{ photons/pixel, SD} = \sqrt{1000} = 33, \ 3.3\% \text{ Noise}$$

With noise being a major and limiting image characteristic with respect to visibility, it must be considered in all phases of the imaging process, from the design of equipment to the selection of methods and adjustments of protocols for specific clinical procedures.

The significance is this, The level of noise in an image can be controlled by radiologists, but it requires knowledge of the factors affecting the noise and the effects of these factors on other aspects of the imaging process especially radiation exposure to patients.

In radiography and mammography, it is the characteristics of the image receptor that determine the noise level as illustrated in Figure 30.

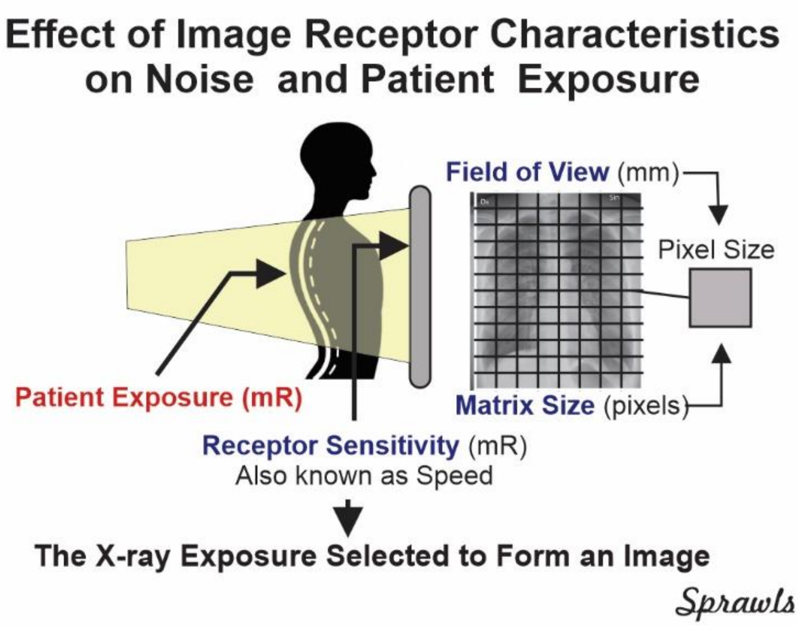

Figure 30. The role of the image receptor on determining visual noise.

The function of the image receptor is to intercept the invisible x-ray beam image from the patient's body and convert it to a form that can result in a visible image. Throughout history there have been two major types--film-screen and digital. The film-screen receptors, used for well over a century, recorded the image on film using fluorescent intensifying screens to give the receptor greater sensitivity or speed. The transition to digital receptors and digital radiography provided many advantages, including more control on the imaging procedure and viewing by radiologists.

With the film-screen receptors virtually all image characteristics (contrast, detail, noise) and sensitivity or required exposure were established by the design of the receptor. In any imaging setting, there is a choice of film-screen receptor types for specific procedures, such as chest or mammography, but not the ability for other adjustments.

Digital radiography provides the radiologist with more control, including the visual noise and patient exposure considered here. *The critical and controllable factor is the average number of x-ray photons captured in each pixel by the receptor.* This is, in turn, determined by two factors: pixel size and the x-ray exposure to the receptor.

In radiography and mammography, pixel size is a design characteristic of the receptors and cannot be changed in the clinic. It is the ratio of the physical field of view (FOV) and the image matrix size (the number of pixels in each direction).

. It is the requirement for visibility of detail (pixel blurring) that is considered in the design of receptors as illustrated here.

	FOV (cm)	Matrix	Pixel Size
Chest	36 x 43	2140 x 1760	0.2 mm
Mammography	24 x 31	2394 x 3062	0.1 mm

The receptor FOV is determined by the anatomical area to be viewed and then a matrix size is selected to provide the necessary visibility of detail. Recalling from Figure 20, a pixel is a blur that combines with the other sources of blurring in a procedure that determines the visibility of detail. The pixel size in mammography is small to provide visualization of the small calcifications.

Here is the great compromise that applies to all imaging methods that produce digital images. Reducing pixel size to increase visibility of detail has the adverse effect of increasing image noise because the smaller pixels capture fewer photons.

The factor that can be selected by radiologists to set the level of image noise is the x-ray exposure used in each procedure. A characteristic of radiographic receptors is the exposure required to form an image. This is generally known as the exposure sensitivity or speed of the receptor. The term “speed” was used extensively for the film-screen receptors where it was picked up from the classification of general photography films. A “fast” film or receptor needed less exposure to form an image. Looking back in time, film-screen receptors were labeled or known by the speed numbers, 100, 200, 400, etc. The lower speed receptors provided higher quality, less blurring and noise, but required higher exposures to the patients. A radiologist could select an appropriate receptor for specific procedures that would provide the necessary image quality with the lowest possible exposure to the patient. The speed of the receptor determined the required exposure which had to be set very precisely. Variation from that specific exposure resulted in either under- or over-exposed films with low image quality and reduced visibility. This was a significant problem with film radiography often requiring repeated examinations to “get it correct.”

A major advantage of digital radiography compared to images on film is a large range of exposure to the receptor that will produce visible images. This characteristic is the *dynamic range* or *exposure latitude* of the receptor. While this is a valuable feature that reduces exposure errors that result in loss of visible contrast, it introduces another image quality issue that must be considered by radiologists.

That is the variation in image noise and radiation exposure to the patient. These two factors must be considered and balanced for each procedure.

Digital radiographic systems are generally programed to deliver specific exposures to the receptor, determined by the type of procedure or anatomical region being imaged. This is a form of automatic exposure control (AEC) so that *receptor exposure* is not an independent factor that must be set by the technologist for each procedure. However, the programed exposure levels for specific procedures can be adjusted as needed.

Radiologists can monitor the exposure used for each image and use that as a guide for balancing image noise and radiation exposure to the patient. All digital radiographic systems calculate a quantity expressing the exposure to the receptor and it is available or displayed along with the image. This is the *exposure index* (EI) with a variety of names and methods for calculating it used by the various manufacturers. The example used here in Figure 31 is the receptor sensitivity or "S" number. Higher numbers represent a higher receptor sensitivity or speed and lower exposure. The deviation index (DI) is a related quantity indicating the relationship of the actual exposure for a procedure to what has been established as an appropriate or target value.

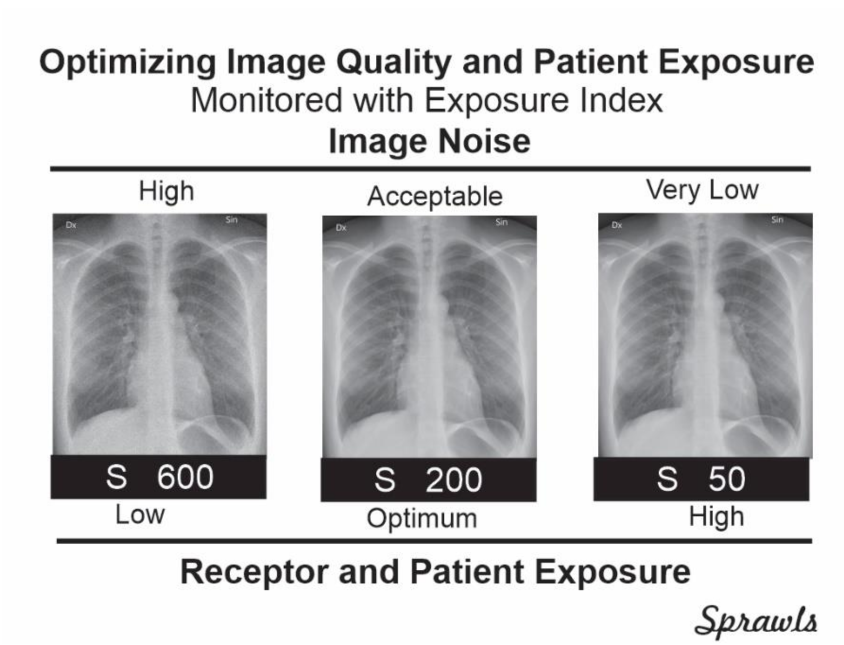

Figure 31. The Exposure Index (EI), in this example expressed as the "S" factor can be used by radiologists to monitor and optimize image quality and exposure to patients.

A first step is determining how the Exposure Index is expressed in the digital radiography systems in one's clinic--then observing values, perhaps discussing with colleagues, and relating values to image quality.

Pixel and Voxel Size in Medical Imaging

The modern medical imaging procedures using digital technology divide the body into small volume elements (voxels) as illustrated in Figure 32.

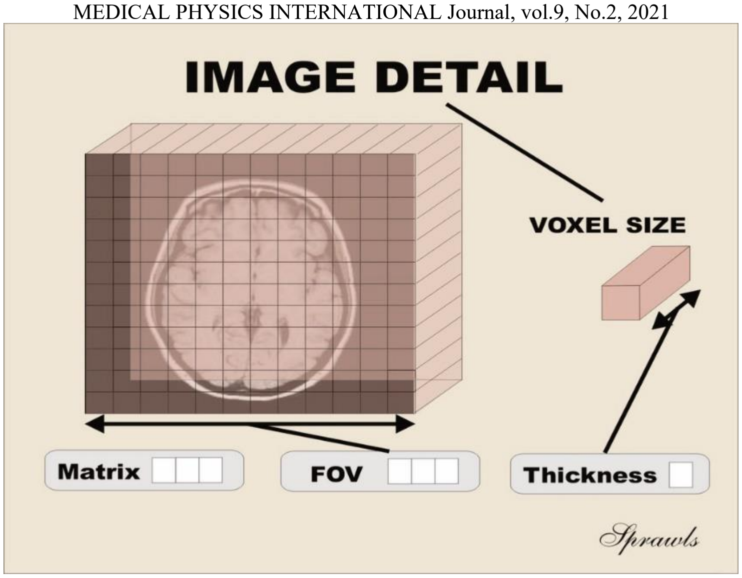

Figure 32. The dividing of the human body into voxels (samples) in the tomographic modalities, CT, MRI, PET, etc.

The imaging process creates numerical values for each voxel relating to the physical characteristics of the tissue: density in CT, magnetization in MRI, radioactivity in the radionuclide imaging procedures. These numerical values then translate into brightness or colors for the corresponding pixels in the image.

The sizes of the voxels and corresponding pixels are critical factors determining visibility, especially as affected by blurring and visual noise, and they have an indirect effect on other factors including radiation exposure to patients (radiography, mammography, and CT) and the time to acquire images (MRI and radionuclide imaging). Voxel and pixel sizes for specific procedures are determined by the combination of factors illustrated in Figure 32. These factors are design characteristics and might vary with each of the modalities (mammography, CT, MRI, etc.) but are often adjustable in setting up protocols for specific procedures.

Optimizing Imaging Protocols

For reference the illustration from Figure 2 is repeated here as Figure 34.

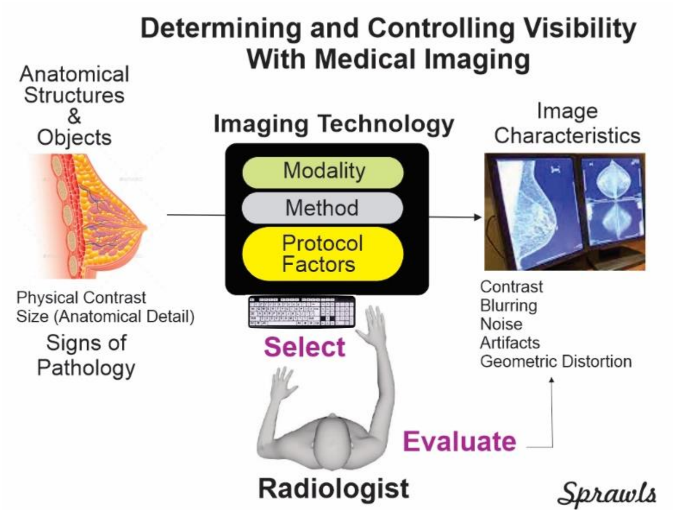

Figure 34. Actions by radiologists to control and optimize visibility for specific clinical requirements.

Optimizing is a critical requirement for an imaging procedure because of conflicts between and among several of the image characteristics and other procedure factors. These include factors associated with the formation of images (KV and MAS, for x-ray, TR, and TE for MRI, etc.) along with voxel/pixel size considered here and illustrated in Figure 35.

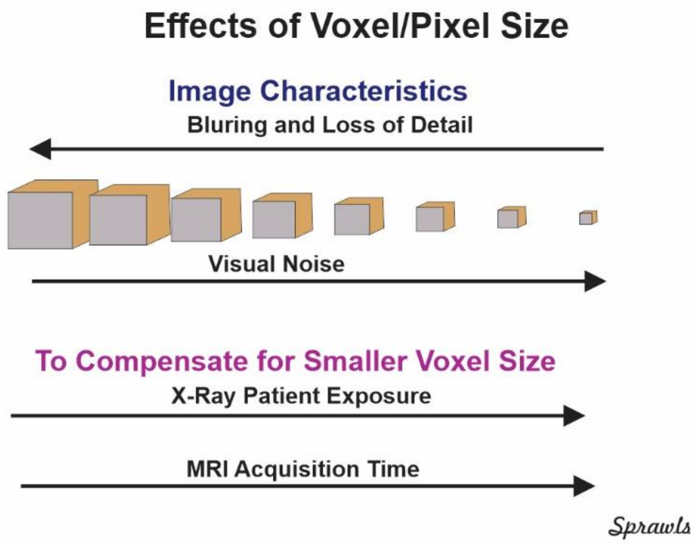

Figure 35. The multiple effects of selected voxel size on visibility and other procedure considerations.

For virtually all the imaging methods the selection of voxel and pixel size is perhaps the most critical factor to be considered in setting up an optimized procedure that provides the necessary clinical visibility in relation to other procedure considerations.

As described previously, a voxel is a blur. In the imaging process it is represented by one numerical value that generally is an average of the physical characteristics (density, radioactivity, etc.) within the voxel all "blurred" together. In all imaging procedures the voxels and pixels are two of the several sources of blurring as illustrated in Figure 22.

An obvious action in setting up an imaging procedure protocol would be to reduce voxel/pixel size to improve visibility of detail in an image. While that is desirable other factors must be considered. As voxel size is just one of the several sources of blurring, as illustrated in Figure 22. there is little to gain with voxel sizes smaller than the other sources of blurring in an imaging system that are related to the design of the equipment this varies among the imaging modalities as illustrated in Figure 8. This ranges from relatively large blurring with the radionuclide imaging methods to very low blurring in mammography.

In selecting an optimum voxel/pixel size there are other factors to consider as illustrated in Figure 35. Reducing voxel/pixel increases visual noise. In x-ray methods (radiography, mammography, and CT) the reduced number of photon interactions in each voxel increases the statistical variation among voxels and the resulting visual noise as described in Figure 19. For the radionuclide/nuclear medicine procedures it is the number of gamma protons produced in each voxel. In MRI the RF signal intensity that counteracts the noise is proportional to voxel size.

In selecting an optimum voxel/pixel size the balance between blurring (visibility of detail) and visual noise is a major consideration. Additional considerations are the increase in radiation exposure to control noise to an acceptable level and potential increase in image acquisition times with some methods, especially MRI.

Image Artifacts

In this context, artifacts are undesirable visual displays, sometimes referred to as "ghosts" that appear in images but are not representations of actual anatomical objects or functions. They are usually unique for each of the modalities and related to the characteristics of the equipment and the imaging process. In virtually all modalities patient motion during the imaging procedure, and foreign objects, especially metal ones, are significant sources of artifacts. With some modalities, especially MRI, there are functions within the imaging process that can be used to reduce artifacts.

Geometric Distortion

Geometric distortion is when an image is not an accurate geometric (size, shape, depth, and orientation) representation of an anatomical structure or region. Unless an artifact, like bright streaks or shadows, covers the image of anatomical objects of interest they do not reduce general visibility.

There is inherent distortion in all radiography and mammography procedures because of the varying geometric magnification as the x-ray beam is projected through the patient's body. This needs to be recognized when evaluating object locations and sizes as displayed in an image.

Conclusion

Maximum visual clinical information that can be obtained using the complexity modern medical imaging methods requires guidance by radiologists with knowledge and experience in matching image characteristics for the required visibility of the structures, objects, and conditions in the human body. This capability will be developed over years of education and experience but can begin by applying the principles described here in ongoing clinical activities.

Curriculum Guide

Class and Conferences for Radiology Residents

On the Topic of

Understanding and Optimizing Visibility in Medical Imaging Procedures

Image Characteristics and Controlling Factors

Objective: Provide Radiology Residents with an opportunity to learn and develop knowledge of the physical characteristic of medical images and controlling factors associated with imaging procedures.

Method: Class and Conference presentations and discussions covering the topics below and augmented with clinical images illustrating characteristics that affect visibility. Review some typical protocols relating factors to image characteristics.

Image Characteristics

Identify and illustrate the five image characteristics.
Contrast
Blurring
Visual Noise
Artifacts
Geometric Distortion

Contrast

Sources of Physical Contrast in the Human Body
Image Contrast
Object Contrast Within Images
Procedure Contrast Sensitivity

Blurring and Visibility of Detail

Example Blurred Images
Effect of Blurring Related to Object Siz
Visibility of Detail
Measuring and Evaluating Blur
Blur Dimensions (Not Easy)
Test Objects/Phantoms (mammography example)
Spatial Resolution
Concept and Significance of Composite Blur
Digital Blurring (Voxels and Pixels)
Comparing the Modalities

Visual Noise
Demonstrate with Clinical Images
Effect of Noise on Visibility of Objects
Source of Noise in X-Ray Images
Measuring and Quantifying Noise (Standard Deviation)
Relation of Noise to Radiation Exposure
Effect of Voxel/Pixel Size on Noise

Optimizing Imaging Procedures
What is Optimization
Factors to Consider
Effects of Voxel Size

Image Artifacts
Show examples and Discuss Sources

Geometric Distortion
Show examples and Discuss Sources

Text: Sprawls P. Understanding and Optimizing Visibility in Medical Imaging Procedures. *Medical Physics International*. December 2021.Addendum
PowerPoint Visuals: Understanding and Optimizing Visibility in Medical Imaging Procedures. *Medical Physics International*. December 2021.Addendum