

OPTIMIZING MEDICAL IMAGE CONTRAST, DETAIL AND NOISE IN THE DIGITAL ERA

P. Sprawls¹

¹ Sprawls Educational Foundation, Montreat, NC, USA, www.sprawls.org

Abstract— Use of digital imaging within all of the medical imaging modalities and methods provides many advantages and values to the practice of clinical medicine. However, the use of digital technology, digital image structure, and the ability to process digital image data in many ways add additional complexity to many imaging procedures. All medical imaging professionals, including radiologists, technologists, and medical physicists must be knowable and experienced with digital imaging in order to obtain maximum values from modern imaging technology and procedures. A common characteristic of all procedures that produce digital images is that the human body is divided into many discrete samples or voxels which are then represented by pixels in the image. The structure of the digital image, especially the voxel/pixel size, has a significant effect on image quality and visibility of structures and objects within the body. The optimization of medical imaging procedure protocols and selection of technique factors requires a comprehensive knowledge of digital image structure, impact on image quality, and the concept and practice of optimization.

Keywords— Digital Images, image quality, protocol optimization.

I. INTRODUCTION

With increasing digital technology in almost all areas of our lives, medical imaging is no exception. The majority of medical images from all modalities are either directly produced or converted into a digital format. This offers many advantages but also challenges in the process of adjusting imaging quality and optimizing imaging procedures for maximum clinical benefit. Medical imaging professionals including radiologists, technologists, physicists, and engineers can be more effective in providing optimized images if they have good knowledge of the structure of digital images and the relationship of that structure to image quality and visibility of anatomy and signs of pathology.

The objective of this article is to review the structure and characteristics of digital images and the impact on three image quality characteristics: contrast, image detail (spatial resolution) and visual noise. These are image characteristics that must be considered together and “balanced” in the process of procedure optimization.

II. THE DIGITAL ADVANTAGE

There are many advantages to having medical images in digital form and it is helpful to review some as illustrated in Figure 1.

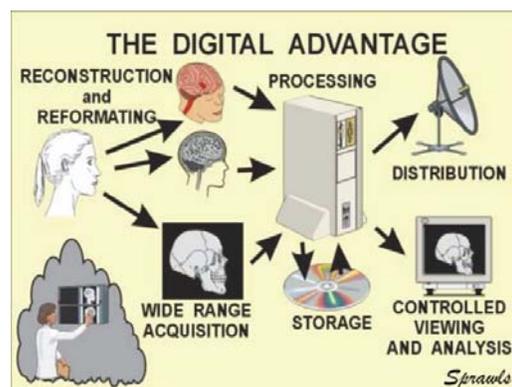


Figure 1. The advantages of medical images in digital form.

Image Reconstruction: The formation (reconstruction) of images with tomographic and 3D modalities--CT, MRI, SPECT, and PET--requires digital computations which result in images in a digital format. Typically the quality characteristics of the digital images can be adjusted when setting up the image acquisition protocols and the image reconstruction that follows.

Wide Dynamic Range or Latitude Acquisition: This applies to all modalities but is especially significant in radiography and CT. When a radiograph is recorded on film there is a very limited range of exposure to the receptor that will produce adequate image contrast and not over- or under- exposed films, This is because of the limited exposure latitude of film relating to the chemical process that records the image. Digital radiographic receptors of all types do not have this limitation and have the advantage of a wide exposure range (dynamic range) in which good image contrast can be captured. This is one of the significant advantages of digital compared to film radiography.

Image Processing: Images in digital format can be processed to alter or enhance specific characteristics. This

can be during the image reconstruction function or later as post processing.

Image Storage and Retrieval: With the advances in digital storage and memory technology and especially the increased capacity, the storage and rapid retrieval of digitized medical images is both possible and practical. This contributes to increased efficiency of clinic operations and improved patient care with the rapid access to images from both current and previous procedures.

Image Transmission and Distribution: The ability to transmit images over networks, from local to global, adds a new dimension to the practice of radiology. It makes images available for viewing and interpretation by qualified medical professionals regardless of where they are located. This is especially significant in acute and emergency cases where a correct diagnosis and guidance can mean the difference between life and death.

Education, Training, and Consultation: Radiology education and training is much more effective and efficient because of the extensive digital resources that are now available. These include teaching files with expanded content and accessibility and extensive online publications, courses, and reference materials. A very valuable feature is the ability of medical professionals to go online and access reference images and information at the time they are viewing images from specific cases. This is providing education at “the point and time of need”.

The full advantage of digital imaging will be realized only when the quality of the images provides the required visualization for the purposes of the procedures being performed. That depends on the knowledge and experience of the medical imaging professionals.

III. DIGITAL IMAGE STRUCTURE

Sampling: A first step in producing a digital medical image is to divide the human body into many individual and discrete samples. Within the body these samples are the *voxels* (volume elements) which are then represented in the image by corresponding *pixels* (picture elements). Generally each tissue voxel is represented by a specific pixel in the image unless some different form of image formatting is used.

Sample (Voxel and Pixel) Size: The size of the individual voxels and pixels is a critical factor in determining image quality and visibility. In most imaging procedures the size is adjustable through a combination of imaging protocol or technique factors that must be considered by the staff conducting the procedure.

Tomographic Imaging and Voxels: For modalities that produce tomographic images of slices (CT, MRI, SPECT, PET) the voxel size is the critical factor. It is determined by the combination of three adjustable parameters as shown in Figure 2.

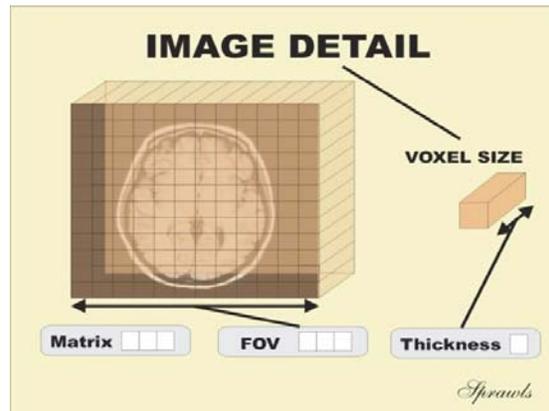


Figure 2. The factors that determine voxel size and related image detail.

The face dimension of the voxel, which closely relates to the corresponding pixel, is determined by the ratio of two factors, the physical size of the imaged area, the field of view (FOV) and matrix size which is the number of voxels/pixels across each dimension of the image.

Field Of View (FOV): First, the distinction must be made between the FOV and image size. The FOV is the physical dimension of the area being imaged at the location within the body. That is significant because two of the image quality characteristics depend on the actual size of the individual tissue voxels and not the size of the pixels in the displayed images.

In most imaging procedures the FOV is adjustable and is set based on the anatomical region to be imaged but with the recognition that reducing FOV does produce smaller voxels and pixels.

Image Matrix Size: The matrix size is the number of voxels and pixels across each direction in the image. Most images are square matrixes with equal dimensions in each direction with sizes that are binary multiples such as 512X512, 1024X1024, etc. There are some applications, especially in MRI, where there are advantages in using rectangular matrixes.

Matrix size is a design characteristic of each of the imaging modalities and within a modality an adjustable protocol or technique factor and is used to control the quality of the images as we will describe in detail later.

Slice Thickness: The thickness of tomographic slices is usually the largest dimension of a voxel and can be adjusted to control image quality.

Projection Imaging and Pixels: The projection imaging modalities--radiography, fluoroscopy, and the gamma camera-- do not form small tissue voxels. The critical factor in determining image quality is the size of the pixel within the body at the location of objects being viewed. It is not the size of the pixel in the displayed image.

Because of the geometric magnification associated with radiographic and fluoroscopic imaging the effective pixel size varies with location within the space between the focal

spot and image receptor. This must be taken into account when considering image quality as illustrated in Figure 3.

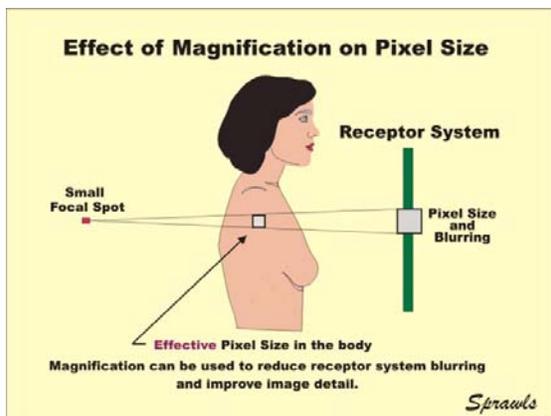


Figure 3. The relationship of image pixel size at the receptor to the sample size within the body.

The ratio of receptor pixel size to the pixel size within the body increases with the geometric magnification. One important factor associated with this is that magnification actually reduces the effective pixel size (tissue sample size) in relation to the fixed pixel size within the receptor. Later we will be seeing that a pixel is actually a source of blurring added to the image. When there is significant geometric magnification the blurring from the receptor is actually reduced at the location that is being imaged within the body. One of the common applications of this principle is *magnification mammography*. It is used to produce images with the least possible blurring and maximum detail especially for visualizing the small micro-calcifications that can be valuable signs of early stage breast cancer. This procedure requires the use of a small focal spot so that the focal spot blurring does not counteract the reduction in receptor system blurring produced with the magnification.

IV. IMAGE QUALITY CHARACTERISTICS

The overall quality characteristic of a medical image is *visibility* of anatomical structures, objects, or signs of pathology that are required for diagnosis and guiding treatment procedures. Visibility of the various objects within the body is determined by a combination of factors as illustrated in Figure 4.

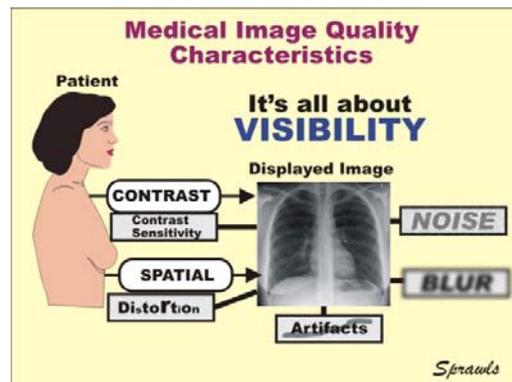


Figure 4. The individual image quality characteristics that affect visibility of structures and objects within the body.

The relationship of visibility to these individual characteristics is somewhat complex and depends on the physical characteristics of the objects within the body. Our objective here is to observe how digitizing an image affects specific characteristics and overall visibility. We will confine the consideration to three characteristics: contrast, detail, and noise, all of which are dependent on the digital structure of images.

Image Contrast and Procedure Contrast Sensitivity: Contrast is the foundation image quality characteristic because without contrast there is no visible image. Contrast originates within the human body as some form of physical contrast, depending on the image modality. The imaging process transforms the physical contrast into visible contrast displayed in the image. Contrast sensitivity (contrast resolution) is the characteristic of the imaging process that determines its ability to “see” the physical contrast within the body. When images are in a digital form processing can be used to enhance and optimize the contrast characteristics.

Image Detail: There is some blurring that occurs in all imaging procedures, including our human vision. The effect of blurring is to reduce the visibility of small objects and structures, anatomical detail. Detail might be referred to as image sharpness and is related to the characteristic spatial resolution that is often measured or calculated to evaluate imaging system performance. Detail is the clinically important characteristic because it determines the smallest objects that can be visualized. It is determined by the physical and design characteristics of each imaging modality and also depends on the adjustment of the protocol or technique factors, including those that affect the digital voxel and pixel size.

Image Noise: Visual noise, a generally undesirable image characteristic, reduces the visibility of low contrast objects and structures. In x-ray and radionuclide imaging it is determined by the concentration of photons captured in the individual digital voxels and pixels. In MRI it depends on the RF signal strength from the individual digital voxels.

Spatial and Geometric Characteristics: Most medical images are produced either by the projection method in

which an x-ray beam is passed through the body projecting an image onto the receptor (radiography and fluoroscopy) or by reconstruction of tomographic images (CT, MRI, SPECT, PET). The major quality issues are the relationship of the areas visible in images to the anatomical regions of interest for specific clinical purposes.

Artifacts: Artifacts, often in the form of streaks, images of things that are not true anatomical structures, “ghosts”, and areas of reduced visibility generally are characteristics of each imaging modality. Some artifacts might be related to the digital structure of images but will not be discussed in this article.

V. DIGITAL CONTRAST ENHANCEMENT

One of the major advantages of digital images is the ability to adjust and optimize the contrast for maximum visibility within the various anatomical regions and tissue compositions and characteristics. This is possible because digital image processing can be performed between the acquired and recorded image and the displayed image. This is a distinct advantage over images recorded on film in radiography where the acquired or recorded image is also the displayed image.

Receptor Dynamic Range and Latitude: This is the characteristic of all imaging systems that determines the range of exposure values to the receptor that will result in the recording of the image contrast coming from the human body. Radiographic film has a limited range of exposure over which it can record an image with adequate contrast. This is the film latitude which corresponds to dynamic range for digital receptors. If the exposure to a film is outside the latitude range, that is either under- or over-exposed, contrast will be diminished or completely absent. Digital imaging methods generally have a wide dynamic range over which full image contrast is recorded.

Pixel Bit Depth: Each pixel in an image is recorded as a binary number which is a multiple of the number two such as 4, 8, 16,256, 512, 1024, 2048,4096. This is known as the bit depth of a pixel. It represents the possible number of different values a pixel can have which determined how many brightness levels or shades of gray will be displayed in an image. A high-quality halftone might have as many as 4096 values..

Pixels with an 8-bit depth can have 256 different values or brightness levels. This can be adequate for an image after processing and ready for viewing but does not provide a wide dynamic range for the image receptors or detectors.

A desirable feature is to have a wide dynamic range for the initial images recorded by the receptor in radiography or for the data captured by the detectors as in CT. This is to ensure that the receptors or detector systems capture the full range of exposures that represents contrast coming from the human body. This reduces the possibility of under- or over-

exposed images with respect to contrast that can often happen with radiographic film.

Image Processing and Windowing: If an image recorded with a wide-dynamic range receptor is viewed directly it would usually appear with very low contrast, a dull gray image. This is because the range of exposure representing the image contrast is small in respect to the total dynamic range that is being displayed. However, an image for display with optimum contrast for specific clinical procedures can be produced by including one or more forms of digital image processing between the recorded or reconstructed image and the image displayed for viewing as illustrated in Figure 5.

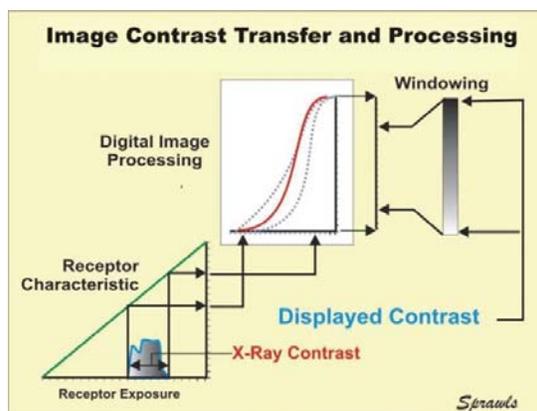


Figure 5. The contrast processing that occurs between the image recorded by the receptor and the displayed image.

In the example shown here the contrast in the x-ray image delivered to the receptor extends over a relatively small segment of the full dynamic range. The important point is that the wide dynamic range does not cut off the contrast, as can happen with film. This provides good image data for processing.

There are usually two things to be achieved with processing.

Look Up Table (LUT) Processing: This gives an image general contrast characteristics that resemble radiographic film. These characteristics are appropriate for specific clinical procedures. This often uses look-up-table (LUT) processing in which pixel values are changed to other values that have been programmed in the tables. Different tables are selected to give an image a specific contrast characteristic.

Windowing: The other action is to select a smaller range from within the wide dynamic range to be the displayed in the image. This has the effect of increasing the image contrast. The range that is selected is designated as the *window* and can be adjusted by the person viewing the image. The window level control places the window within the larger dynamic range and the window width control determines the range of pixel values that will be displayed in the image. The width is very much an image contrast

control. Decreasing the window width increases visible contrast in the displayed image.

VI. DIGITAL IMAGE BLURRING AND DETAIL

Visibility of anatomical detail and small objects within a body is limited by the blurring that occurs during the production of an image. There are several sources of blurring within each imaging modality and some of these are adjustable when setting up an imaging procedure. Focal spot size is an example. In radionuclide imaging there is blurring associated with the design of the collimators.

Digitizing an image is a blurring process because all details within a pixel area are blurred together and displayed as one pixel. When viewing a digitized image we see an array or matrix of pixels but cannot see any detail within the individual pixels. In the tomographic imaging modalities the voxels are three-dimensional (3D) blurs. While the digitizing process of dividing the body and imaged area into discrete samples, as previously described, does introduce an additional source of blurring it does not significantly reduce image quality and visibility if the imaging factors are adjusted appropriately and optimized. With respect to selecting voxel and pixel sizes to adjust the blurring there are two relationships that should be considered. One is the relationship of the voxel/pixel blurring compared to the other sources of blur within the imaging process and the other is the effect of voxel/pixel size on image noise. Both of those relationships will now be considered.

Other Sources of Blurring: Within each medical imaging modality and procedure there are several sources of blurring, usually associated with the image acquisition phase, which generally comes before the digitizing process. Those sources are characteristics of each imaging modality (radiography, CT, MRI, etc.) and associated with the equipment design and operating factors. This might be referred to as the pre-sampled blurring or spatial resolution. Here we will not go into the detail for each modality but will consider a representative imaging system illustrated in Figure 6.

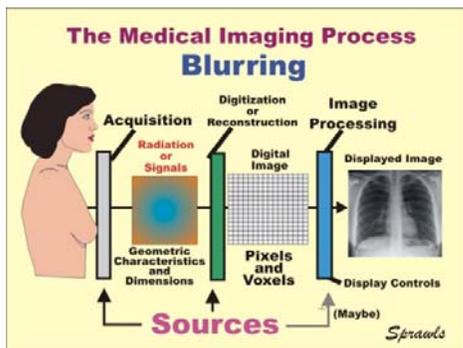


Figure 6. Sources of blurring common to all imaging systems.

Our specific interest here is the blurring introduced by the digitizing process in which the body is divided into individual samples, the voxels and pixels, each one is a blur. The size of the voxels and pixels, and the resulting blurring, can usually be adjusted when setting up the imaging procedure protocol or technique factors. This is by selecting values for the FOV, matrix size, and slice thickness. The question, what is the most appropriate and the optimum voxel and pixel size for a specific procedure?

Comparing Blur for the Imaging Modalities: There is a general range of blur values associated with each imaging method as illustrated in Figure 7.

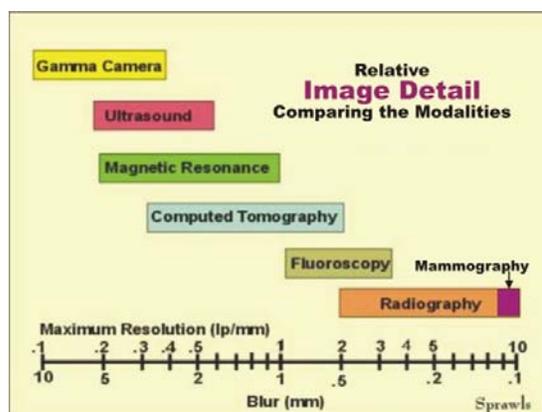


Figure 7. The general range of blur values for each of the imaging modalities.

Each imaging modality is characterized by the limits to the visibility of detail that can be achieved because of the blurring associated with the imaging process. This characteristic is related to and sometimes measured or evaluated in terms of spatial resolution. The general values shown here represent the total or composite blur produced by both the physical design of the equipment (focal spot, detectors, collimators, etc.) and the digitizing process.

Optimum Voxel/Pixel Size: A fundamental question is how should voxel/pixel size be adjusted and matched to the other sources of blur within the imaging process? Should the voxel/pixel size be set to the smallest possible value in order to minimize blurring and give the best visibility of detail? The relationship is illustrated in Figure 8 for radiography but the principle applies to all modalities.

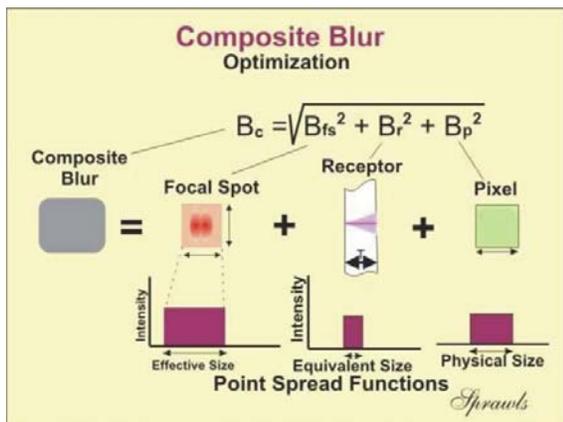


Figure 8. The combining of blur values.

The total blur that occurs during an imaging procedure is the composite, or sum, from all sources. Radiography is illustrated here but the principle applies to all modalities; only the sources of blurring are different. The physical dimensions of a blur are often expressed as point spread functions. Because of the complexity of the shape and intensity distributions blur dimensions are often expressed as “effective” or “equivalent” sizes, which relate to their ultimate image quality characteristics. This corresponds to the actual physical dimensions of voxels and pixels. This approach to analysis in the spatial domain rather than in the frequency domain, which uses modulation transfer functions (MTF), is very helpful for comparing the sources of blur and understanding the process of optimization. A reasonable estimate of the composite or total blur can be calculated using the root mean square as shown rather than the more complex mathematical process of convolution integration.

Our interest here is considering pixel size in relation to other blur values and what an appropriate or optimum pixel size is.

The Smallest Possible Pixels? An initial thought might be that pixels should always be made as small as possible because they are additional sources of blurring in an imaging procedure. As we are about to consider, that is not the best approach. There are several reasons for adjusting pixel and voxel sizes to larger values than what is physically possible with the specific imaging technology.

A major factor is that when pixel size is set to significantly smaller values than the blur from other sources there is diminished improvement in image detail. The blurring from the other sources becomes the controlling factor.

However, with most of the imaging modality the factor that is contradictory to reducing voxel/pixel size is image noise.

VII. DIGITAL IMAGE NOISE

Producing an image in digital form and dividing the body into voxel and pixel samples does not introduce or add noise but is a major factor in controlling the noise coming from other sources within the imaging process. This relationship is illustrated in Figure 9.

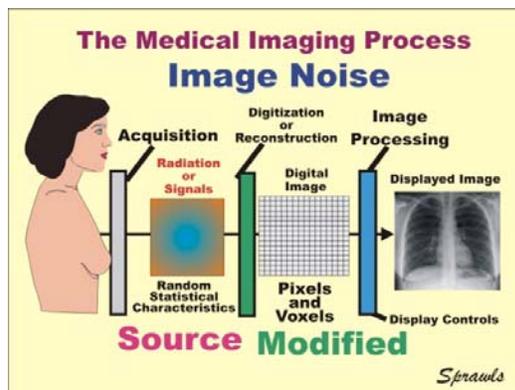


Figure 9. The relationship of digital image structure to the sources of image noise.

Quantum Noise: For both the x-ray and radionuclide imaging modalities the major source of image noise is the random distribution of photons that is captured in each sample (voxel or pixel) to form the images. The noise value, sometimes expressed as the standard deviation of the concentration of captured photons, is inversely related to the photon concentration or receptor exposure. For the digital imaging methods the “critical number” with respect to noise is the number of photons captured in each voxel or pixel as illustrated in Figure 10.

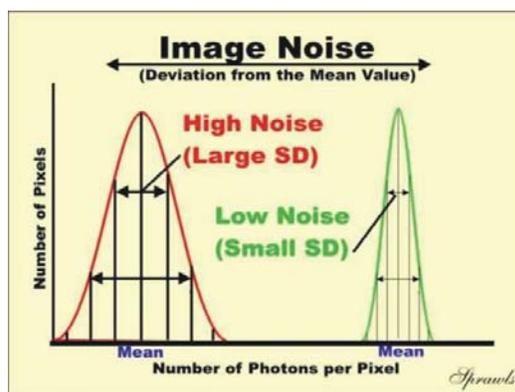


Figure 10. The relationship of image noise to the number of photons per pixel, or receptor exposure.

There are two approaches to decreasing noise by increasing the number of photons per pixel. One is to increase the exposure delivered by the x-ray beam or radionuclide and the other is to increase the size of the

voxels and pixels. Both of these have adverse effects on other factors. The first generally leads to increased radiation dose to the patient and the second contributes to decreased image detail. These are the major factors that require consideration in the process of *optimizing* imaging procedure protocols.

MRI Signal to Noise: Noise is also a limiting factor with MR imaging. Although the source of noise is very different from that with photon imaging, voxel size is also a controlling factor. Since MRI uses RF signals the intensity of the signals, or signal strength, plays a major role in the amount of noise that appears in an image. Noise in an image is decreased by reducing RF noise radiation from the body and by having a stronger RF signal coming from the tissue being imaged, or increasing the signal-to-noise (S/R) ratio. There are several approaches to decreasing the noise component including RF coil design and selection, signal averaging, and the receiver bandwidth adjustment. However, it is the signal strength, not the noise radiation, which is related to voxel size.

Every Voxel is a Signal Source: During the MR imaging process the body is divided into individual voxels. During the acquisition phase of the procedure the combined actions of the slice selection, phase encoding, and frequency encoding gradients give the signals from each voxel unique values so that during the reconstruction phase the signal from a specific voxel is displayed in the corresponding image pixel. The brightness of a pixel relates to the strength of the RF signal from the voxel. Image contrast is produced by the differences in RF signal strengths between the various tissues and anatomical areas. Image noise, however, is determined by the overall or average signal strength throughout the imaged area.

The signal strength is determined by the level of tissue magnetization within each voxel which ultimately depends on the quantity of magnetic nuclei (typically protons) within a voxel. For a specific tissue this is directly determined by voxel size.

When setting up an MR imaging protocol and selecting voxel size, it is a direct control on RF signal strength and the noise that will appear in the image.

Conflicting Requirements: Now we see a problem! Increasing voxel size for the purpose of decreasing image noise can have the adverse effect of increasing image blurring and reducing visibility of detail. That conflict is present in all modalities and methods that produce digital images and is one of the major issues to be considered in optimizing imaging procedures.

VIII. OPTIMIZING DIGITAL IMAGING PROCEDURES

In the process of setting up an imaging procedure protocol and selecting technique factors there are always conflicting requirements. With x-ray and radionuclide procedures there is the need to balance image quality with

radiation dose to the patient. With MRI this compares to the general conflict between image quality and the desire for faster image acquisition which has significant clinical advantages.

While setting up an optimized protocol usually begins with the non-digital factors such as adjusting the x-ray spectrum, control of scattered radiation, selecting RF coils in MRI, etc., it often includes the selection and adjustment of voxel and pixel sizes. That is the focus of our attention in this discussion. To help us in visualizing the relationships and communicating with others we will use the analogy of a football game as illustrated in Figure 11.



Figure 11. The Conflicting Goals in an Imaging Procedure.

In a football game our team has only one goal to move the ball toward. That makes it simple; just requires skill and much physical effort! In medical imaging it is complex because “our team” has several competing goals as illustrated. Each imaging protocol or set of technique factors is represented by a position of the ball somewhere on the field. By changing factors the ball can be moved closer to one of the desirable goals. The challenge is that as we move closer to one goal we are moving away from the other goals. That is the problem we face in optimizing imaging procedures.

What is Optimum Image Quality? That is a universal question throughout medical imaging. The answer for the most part comes from the combined and shared experiences of medical imaging professionals, especially radiologists, who have determined the image characteristics necessary to provide adequate visibility for the various clinical applications. Physicists contribute by providing knowledge about the specific image quality factors and their relationships to imaging methods and technology.

General image quality requirements along with imaging protocols and techniques for various clinical procedures are part of the “common knowledge” within the practice of radiology and supported by a variety of educational resources and references. While this provides a foundation for imaging there is still the opportunity to more fully optimize imaging procedures for variations in clinical requirements and patient characteristics. That requires an

understanding of the effect of the digitizing process on image quality.

Evaluating Clinical Image Quality: A first step in optimizing digital image quality is to evaluate images that are being produced. This requires consideration of at least the three characteristics, contrast, detail, and noise. The contrast can usually be adjusted as the image is being viewed (by windowing) but detail and noise are typically established during the acquisition and reconstruction of images. Consultation among the radiologists, technologists, and medical physicists can determine if the detail and noise is appropriate or needs to be changed.

Digital Imaging Procedure Optimization: With knowledge of image quality requirements for specific imaging procedures and the evaluation of images that are being produced, the imaging team can engage in the process of “continuing quality improvement” and the balance of image quality with other requirements such as managing radiation dose and image acquisition time.

IX. CONCLUSIONS

The incorporation of digital imaging within the medical imaging modalities provides many advantages and values but also major challenges. The digitizing process has a

significant effect on image quality in several respects. Because of the opposing effects, especially between detail and noise, imaging procedures must be optimized for maximum clinical benefit.

The ultimate value of digital imaging in medicine will be obtained only when these concepts and practices are included in education and training programs for radiologists, technologists, medical physicists, and engineers.

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Contacts of the corresponding author:

Author: Perry Sprawls
Institute: Sprawls Educational Foundation
Street: 130 Kanawha Drive, PO Box 1208
City: Montreat, NC 28757
Country: USA
Email: sprawls@emory.edu