# DIGITAL ELEMENTS, IMAGE QUALITY, RADIATION EXPOSURE, AND PROCEDURE OPTIMIZATION

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*Abstract* — **The complex relation between digital image elements, blurring, noise and radiation exposure provides the opportunity for medical physicists to expand their professional activities from a focus on equipment function and safety to supporting the optimization of imaging procedures with a balance of image quality characteristics and radiation dose. This is being achieved with the enhancement of medical physics programs, for both physicists and other medical imaging professionals, to add emphasis to the effects of digitization on all aspects of image quality and the complex process of procedure optimization. The objective of this article is to contribute to the educational process for both medical physicists and other medical professionals with a focus on the characteristics of the digitizing process and its effects on image quality and related factors, with the goal of developing optimized clinical procedures.**

## I. INTRODUCTION

The continuing development of medical imaging as a major clinical diagnostic method and the associated medical physics is defined by two major “landmark” events as illustrated in Figure 1.

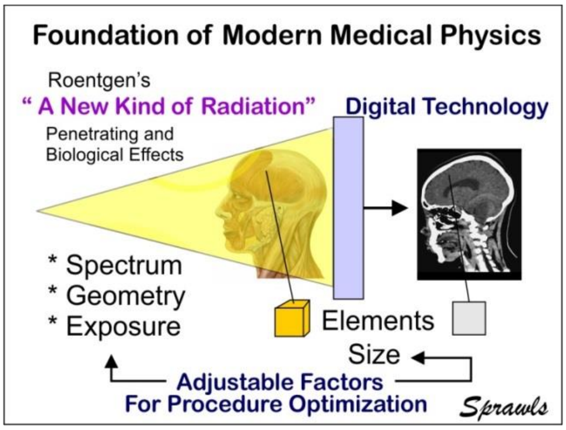


Figure 1. Two developments that form the foundation on which modern medical imaging methods are based.

The first was the discovery of “a new kind of radiation” and investigation of its properties by Roentgen in 1885. It was the radiation that could penetrate the human body, form images, and produce biological effects. This was soon followed by the discovery of radioactivity and radiations with similar properties. For almost a century both imaging and therapeutic applications developed and evolved based on the properties of these radiations. The practice of clinical medical physics and medical physics education was devoted to the characters of these radiations and the process of producing and controlling the radiation for both optimum imaging and therapeutic procedures.

The second was the development of digital technology with its major impact on society, including medical physics and clinical medicine. This was well underway in the 1970s and was a defining factor in the beginning of the second century of applied medical physics in the 1980s. Digital technology provided a foundation for image reconstruction from acquired data and made possible the development of the modern tomographic imaging methods--CT, MRI, SPECT, and PET--with the additional values of digital procedures for processing image to enhance quality, transmission, storage and retrieval and controlled display and viewing. Digital technology also contributes to radiation therapy, beginning with images and methods for treatment planning and controlling and optimizing procedures, such as IMRT, for effective treatment of cancer. However, in this article we confine consideration to the field of medical imaging, the author’s area of experience.

Modern medical imaging and the associated medical physics is now the combination of two major realms, *radiation* and *digital technology*. Within each realm there are many controllable factors that must be considered to produce both diagnostic imaging and therapy procedures that are the most effective for each patient procedure.

A continuing challenge is that many of the adjustable factors have effects on several image quality characteristics and radiation exposure to patients, and these are often conflicting and opposing effects! An appropriate goal is to take the conflicting effects into account and for each patient procedure, diagnostic or therapy, develop a protocol or combination of adjustable factors that is *optimum* for that particular patient’s clinical needs.

## II. CLINICAL PROCEDURE OPTIMIZATION

Procedure optimization is an applied physics process. In *therapy* it is within the context of treatment planning and verification conducted directly by a physicist. In diagnostic imaging where a physicist is not directly involved with each individual patient procedure the role of a physicist is that of consultant to the clinical staff and as an educator. It is usually a radiologist who selects a protocol for a specific procedure, based on personal experience and professional references. However, there is a need for knowledge of physics and technology in order to understand the various protocols, their relation to image characteristics, and especially to the visualization of conditions within a patient body along with effects on factors including radiation dose to a patient.

The objective of this article is to contribute to the educational process for both medical physicists and other medical professionals with a focus on the characteristics of the digitizing process and its effects on image quality and related factors, with the goal of developing *optimized clinical procedures*.

## III. THE DIGITIZING PROCESS AND ELEMENT SIZE

The major impact of applying digital technology in medical imaging and therapeutic procedures is that the patient body is divided into many individual small sample elements, voxels, and corresponding image pixels, with each represented by a numerical or digital value. It is the size of these elements that has a major effect on image quality and factors including radiation exposure and image acquisition time in many procedures. In principle, there is an optimum or "best" digital element size for each imaging procedure. This is determined by a combination of factors including the technical characteristics and design of the imaging systems, the physical characteristics of the anatomical structures, and signs of pathology within a patient's body. The adjustment of protocol factors including element size for each imaging procedure must take into account both the characteristics of the technology and the visualization requirements within the patient body as illustrated in Figure 2. As we will discuss later, it is the element size for a specific procedure that affects visibility within the body.

In projection imaging methods, especially digital radiography, mammography, and fluoroscopy, the design of the receptor generally determines element (pixel) size with some effect relating to the selected field of view (FOV). For the tomographic imaging methods (CT, MRI, SPECT, PET) element (voxel) is determined within the reconstruction process by a combination of adjustable protocol factors.

While some design characteristics of the imaging equipment (focal-spot size, collimation, receptor/detector thickness, etc.) do not directly determine element size they do establish ranges or limits on what would be an optimum element size for a specific imaging method.

*It is the imaging elements, voxels and pixels that establish the major relationship between the design of the equipment and the optimization of clinical imaging procedures.*

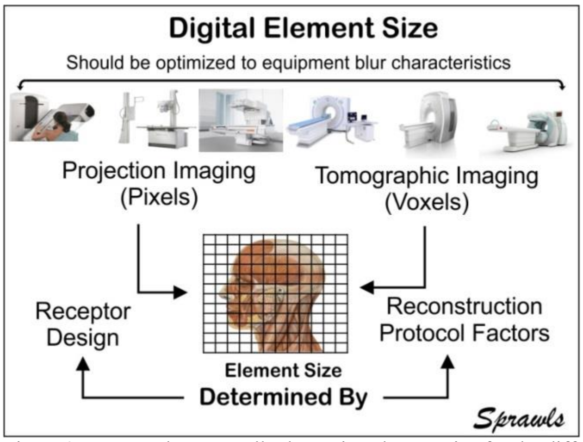


Figure 2. Factors that generally determine element size for the different imaging modalities.

Imaging element size varies over a considerable range covering the different modalities and relates to the design of the technology and the specific clinical applications. With each imaging modality or method, for example CT, the element size can be adjusted by the clinical imaging staff in the context of the imaging technique or protocol. It is these adjustments that can have a significant impact on image quality and other factors including radiation exposure to a patient. Voxel size is determined by the combination of three factors as illustrated in Figure 3.

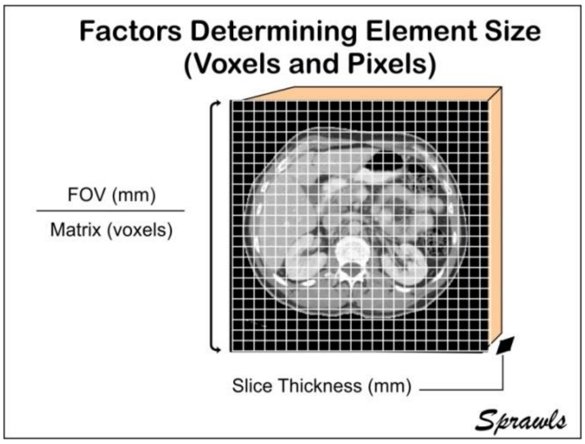


Figure 3. The three often adjustable factors that determine digital element size.

It is the ratio of the field-of-view (FOV) to the numerical size of the matrix that determines the "face" dimension of a voxel or pixel size in an image. For the tomographic imaging methods it is tissue voxel size, not displayed image pixel size, that determines image quality and visibility within the body. The significance is that the FOV within the patient's body is what affects mage quality. With many imaging methods the FOV is an adjustable technique or protocol factor. Using a smaller FOV reduces voxel or pixel size with the expectation of reducing digital blurring and improving visibility of detail as described later.

## IV. Image blurring

Blurring is the image quality characteristic that is directly affected by the digitizing process. All anatomical detail and structures within a voxel or pixel are "blurred together" and represented by one numerical value such as a CT number. The size and shape of the digital element defines the dimensions and characteristics of the blur. This digital blurring is in addition to the blurring from other design characteristics of the imaging technology such as focal-spot size, receptor thickness, and collimators in gamma cameras. This blurring is perhaps the most significant characteristic of digital imaging methods that relates and matches equipment design to optimized clinical procedures.

The fundamental question is this: what is the most appropriate element size for a specific clinical procedure? For this there is no simple answer because it depends on a combination of several complex relationships which we will now consider.

The general advantage and goal of reducing element size and the related blurring is to increase visibility of anatomical detail and signs of pathology. However, reducing element size and the associated blurring is limited by two factors. One is the design of the imaging equipment and the other is image noise considerations when adjusting imaging procedure protocols to be discussed later.

*Imaging Equipment and Composite Blurring*

All medical imaging methods produce blurred images. The range of blur values is an inherent characteristic of each modality, related to how images are formed and the design of the equipment. This ranges from very small blur values in mammography to significantly larger values with the several radionuclide imaging methods. This is sometimes designated as the "pre-sampled" blur (resolution) to distinguish it from the blurring produced by the digitizing (sampling) process.

For virtually all modern medical imaging methods the blur that is present in the image is a composite of blur values from several sources. The two major ones are the equipment and the digitizing process as illustrated for computed tomography in Figure 4.

For each imaging method and procedure there is a combination of factors that determine the amount of blurring in an image. The challenge is determining the *optimum combination* of design and protocol factor values. Computed tomography (CT) is an example. All imaging equipment is limited as to the lowest possible blurring because of several competing characteristics. With all x-ray methods focal-spot size is a major factor. Blurring is reduced by using smaller focal-spot sizes but this limits heat capacity and the ability to perform many types of procedures. The illustration in Figure 5 will now be used to develop both a conceptual understanding and the quantitative relationships determining composite blurring for an imaging procedure using digital radiography as an example.

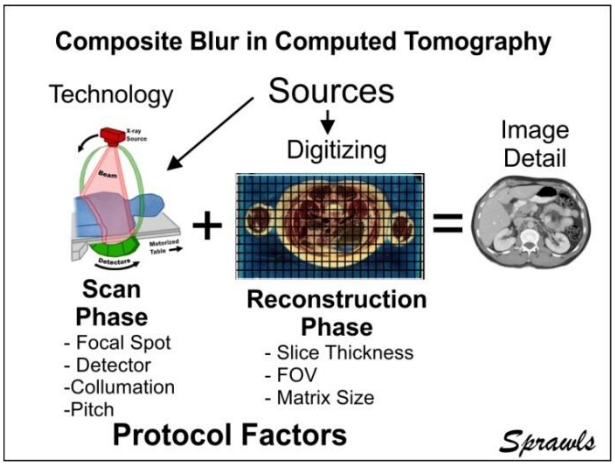


Figure 4. The visibility of anatomical detail in an image is limited by the composite blur from both the equipment design characteristics and the formation of the image in a digital format.

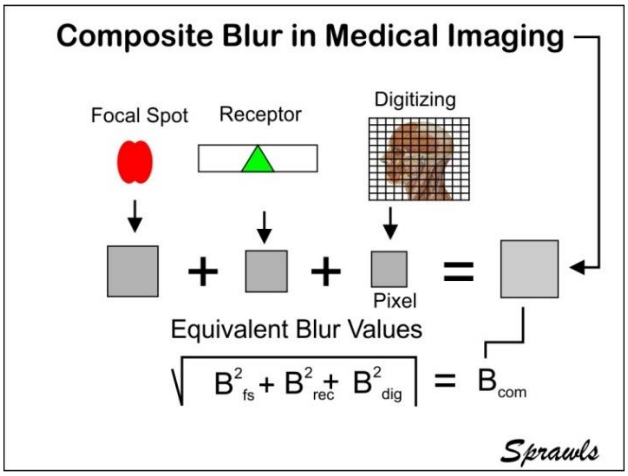


Figure 5. Sources of blur: focal spot (Bfs) , receptor (Brec) , and digitizing (Bdig) that combine to form the total or composite blur (Bcom) within an image.

In all medical imaging procedures the blur in the image is a composite, or combination, of the blur from several sources within the imaging process. The formation of an image in a digital format is one source with each voxel or pixel being a blur. Our specific interest is in deterring the appropriate or optimum size of the element for a specific imaging procedure. As described previously, this is determined by a combination of factors including the technical characteristics and design of the equipment and the image quality characteristics required for specific clinical procedures along with other issues including radiation exposure and imaging acquisition times.

Here we are considering the relation of element size to the technical characteristics of the equipment using radiography as an example as illustrated in Figure 5 where several sources of blurring are shown. With most imaging technology there are usually compromises and tradeoffs with other requirements.

Focal spot size is an example. Increased focal spot size increases x-ray tube heat capacity permitting the exposures required for many clinical procedures. This also increases blurring. For most radiographic procedures, including mammography, focal spot sizes for most procedures are established. These range from approximately 0.1 mm for magnification mammography to as large as 1.5 mm or more for thoracic and abdominal imaging.

For most radiographic receptors the thickness of the x-ray absorbing material is a source of blurring. Thicker absorbing materials require less exposure to produce an image but also result in increased blurring.

The blur produced by focal spots and receptors has specific shapes and spatial distributions. The blur produced by a focal spot is actually an image of the focal spot itself. The blur within a receptor is more of a Gaussian distribution. This becomes a factor when considering the contribution of each to the total or composite blur and including the blur produced by the digitizing of an image.

*Effective Blur Values*

*The effective value of a blur in medical imaging is defined as the dimension of a square or rectangular blur with uniform distribution that has the same general effect on image quality and visibility as the actual blur from the various sources.*

In digitized images the dimensions of the voxels and pixels are the effective blur values. The size of a focal spot measured with a star pattern is not the actual physical size but the effective size that can be used to determine the effective blur for a procedure. For receptors the effective blur can be calculated from the MTF.

Here we are not focusing on the precise blur values from the various sources but a more comprehensive model of how the blur from the different sources, including digitizing, can be combined to estimate the composite blur (Bcom) for a procedure. An approximation and generally used relationship is illustrated in Figure 5

There are several significant observations to be made. First, the blurs do not add numerically but it is a process of convolution with the blurs from the different sources somewhat superimposed or overlapping. Another factor is reducing the blur from one source does not have an equal effect on the composite or total image blur because it is combined and “weighted” by the blur from the other sources.

Now to the issue of what is the best digital element size for a particular imaging procedure as it relates to the equipment. A general “rule of thumb” is there is no significant advantage in having element sizes smaller than the blur from the other sources within the imaging process. It is the technical design of the equipment that establishes a limit on the advantage of reducing element size to reduce blurring and improve image detail.

## V. Image noise

Noise is related to element size. This makes noise a major factor in selecting or adjusting element size for specific clinical procedures.

*Quantum Noise*

There can be several sources of noise within the various medical imaging methods but quantum noise is in almost all cases the most predominant. This is appropriate because quantum noise relates to radiation dose to patients. In an optimized imaging procedure the objective is not to reduce noise to the lowest possible value but to a value that is acceptable for the specific clinical diagnostic requirements. Reducing the noise below this would generally result in unnecessary radiation dose to patients.

The actual source of the quantum noise is the natural random distribution of photons within an x-ray beam or from radioactive sources. However, the range of the photon distribution within an image area is also determined by the digitizing process, specifically the size of the digital elements.

The general concept of digital image noise is illustrated in Figure 6.

The random variation in the number of photons from pixel to pixel illustrated here is generally represented by a Gaussian distribution with a standard deviation (SD) value equal to the square root of the mean number of photons attenuated in each element. The SD, expressed as a %, is a useful parameter for expressing the noise level. Most digital imaging methods, especially CT, have the capability in the software to calculate and display the SD for a region of interest (ROI) selected by the operator. This can be used to obtain quantitative noise values for specific imaging protocols and used to optimize procedures.

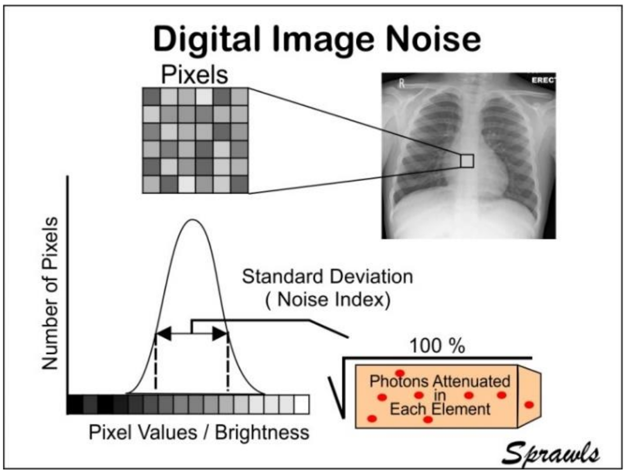


Figure 6. A magnified area within an image showing the random distribution of pixel values as the source of noise.

*Element Size and Image Noise*

As we have observed, the process of creating images in a digital format involves the segmenting of both the patient body and the image into a matrix of voxels and pixels. It is the size of these elements that has a major effect on two quality characteristics, blurring (detail, resolution) and image noise with an indirect effect on factors including radiation dose to patients and acquisition time for some procedures. Here we will now consider the effect of element size on noise using Figure 7.

Figure 7. The two factors--element size and radiation dose--that determine noise in digital images.

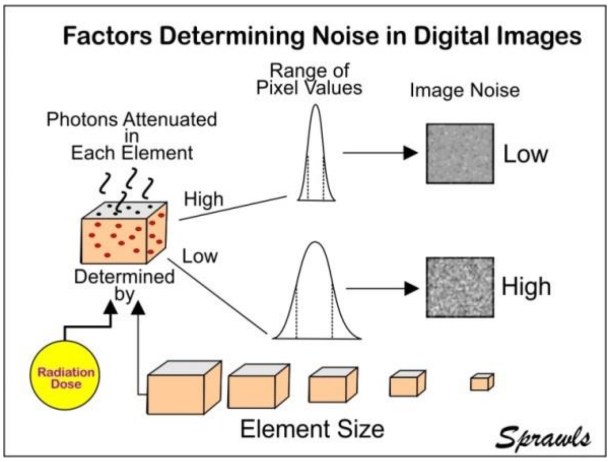


Figure 7. The two factors--element size and radiation dose--that determine noise in digital images.

In virtually all medical imaging methods the size of the digital element is a major factor in determining image noise. This includes methods using ionizing radiation (x-ray, gamma, etc.) and MRI but for different reasons.

The random variation in the number of photons from element to element, the source of the noise, depends on *the number of photons* attenuated in each element as we have seen. This is determined by the product of two factors, the concentration of photons (radiation dose) and the size of the element. It is the size of the elements that causes the conflict between the two image quality characteristics, blurring and noise. As we have seen, increasing element size increases blurring but has the desirable effect of decreasing noise. This is one of the major issues that must be considered in adjusting and optimizing imaging procedures for specific clinical objectives. Combined with this is the third factor, the radiation dose to the patient.

## VI. NUCLEAR MEDICINE AND MAGNETIC RESONANCE

Up to this point we have focused on the x-ray imaging methods where a common factor is the radiation dose to patients that directly relates to image noise. This direct relationship does not exist for the other imaging methods but there are compromising factors determined by selected element size that must be considered when optimizing a specific imaging procedure.

In nuclear medicine imaging the photons per pixel acquired that affects image noise is determined by the concentration of radioactivity within the patient body and the time devoted to acquiring the image data. Both involve compromises. The concentration of radioactivity has a direct effect on radiation dose to the patient. While lower concentrations of radioactivity and dose can be compensated to some extent with increased acquisition and scan times this can limit some imaging capabilities. Selecting a digital element size for a procedure relates image quality to the both radiation dose and required acquisition time.

With magnetic resonance imaging (MRI) radiation dose is not an issue and the compromise determined by voxel size is the relation of image quality to image acquisition time. This is significant because MRI requires relative long acquisition times for many procedures and acquisition time is related to selected voxel size as illustrated in Figure 8.

Data for the reconstruction of MR images are acquired using two encoding methods, frequency and phase, for the radio frequency signals. The basic acquisition time is determined by the image matrix size in the phase encode direction. Although there are modifying factors (signal averaging, fast imaging methods, etc.) Each line of voxels in the phase encode direction requires one cycle or time interval (repetition time –TR) in the acquisition process. Acquisition time can be reduced by reducing the number of lines in the matrix which results in increased voxel size if the field of view is not changed. This reduction is a compromise between acquisition time and image blur.

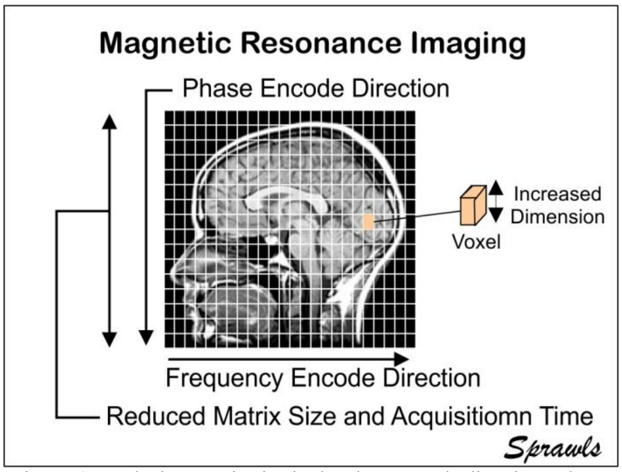


Figure 8. Reducing matrix size in the phase encode direction reduces acquisition time but results in a larger voxel dimension and reduced detail.

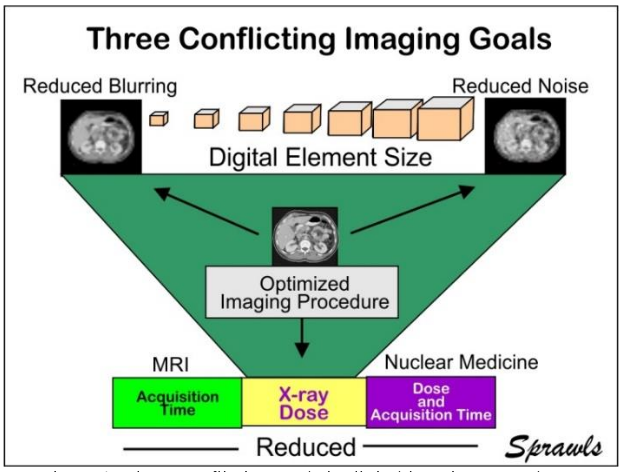


Figure 9. Three conflicting goals in digital imaging procedures: reducing image blurring and noise in relationship to radiation dose and required acquisition time.

## VII. THE OPTIMIZED DIGITAL IMAGING PROCEDURE

A major goal of every medical imaging procedure is that it is *optimized* to have the necessary image quality to provide the required clinical information and without unnecessary radiation dose, image acquisition times, etc. A complicating factor, especially for images in a digital format, is the conflicting image quality characteristics illustrated in Figure 9.

With images in a digital format, now including most medical imaging modalities, the element (voxel and pixel) size covers a very large range and has a direct impact on two image quality characteristics along with an indirect impact on other significant factors. The three conflicting or opposing goals affected by element size are illustrated in Figure 9. We will now consider a general approach and process leading to an optimized imaging procedure with special attention on digital element size. This will be developed in three steps: factors determining image blurring, noise, and then radiation dose to a patient or acquisition time.

*Image Blurring, Detail, and Resolution*

It is appropriate to begin with blurring because the digitizing process adds blur to images. Reducing element size can be used to reduce this source of blur. However, as described and illustrated previously, there is a limit to the value of reducing element size because of the other sources of blur within the imaging equipment. Typical element sizes for each imaging modality are generally "matched" to the other sources of blur. A defining image quality characteristic of each imaging method or modality is the visibility of anatomical detail (spatial resolution) that can be achieved. This is a factor in determining the specific clinical procedures the modality is used for. Here are two examples. One of the clinical objectives with mammography is to visualize extremely small, or micro-, calcifications that can be signs of early breast cancer. This requires an imaging process with very low blurring and digital elements (pixels) as small as 0.05mm. The nuclear imaging methods, including SPECT and PET, are used to visualize larger regions of tissue and elements (voxels) with dimensions as large as 5mm used. For the digital elements in medical imaging this is a range of 100 to 1.

*It is the clinical requirement for visualizing different levels of anatomical detail and small signs of pathology that is a factor in selecting a specific imaging modality and the associated digital element size.*

*Digital Image Noise*

With a digital element size for a specific imaging procedure determined by the visibility of detail requirements and the design of the equipment a next step is to consider and control the noise in an image. As described previously, for a specific element size the noise is determined by the number of photons attenuated in the element. This generally relates to dose in tissue voxels in tomographic or exposure to receptors in projection imaging methods. With respect to radiation to a patient it is desirable to reduce these to "acceptable" values. And that raises a major related question: "What is an acceptable level of noise in a specific medical image?"

The impact of noise is that it reduces visibility of *low-contrast* objects and structures within the body. While this is different from the effect of blurring that reduces visibility of small objects and anatomical detail, many small objects also have low contrast and their visibility is also reduced by image noise.

As described before, the inherent sources of blur (focal spot, receptors, etc.) within imaging systems establish a limit to the improvement in image detail that can be achieved by reducing digital element size. The other factor that must be considered in reducing element size is that it increases image noise.

*With the digital element size for a specific clinical procedure generally fixed by the physical characteristics of the equipment and requirements for image detail the controlling factor for noise becomes the quantity of radiation photons used to form the image*.

With the x-ray imaging methods it is the relationship of noise to radiation exposure that requires considerable effort in optimizing. The objective is not to reduce noise to the lowest possible level. It is to set the noise to an *acceptable level* for a specific clinical procedure. This can be done by collaboration between medical physicists and radiologists. With their knowledge of the clinical conditions and visualization requirements along with experience, radiologists are in a position to decide on acceptable levels of noise. The medical physicists can then analyze the factors affecting the noise with an emphasis on radiation exposure. Determining the radiation exposure or dose to patients and comparing to established references and guidelines gives some indication if a procedure is optimized with respect to noise and radiation.

A special opportunity for medical physicists through education and consultation is providing other medical imaging professionals with an understanding of the relationship of noise to radiation exposure. Radiologists like visually appealing images with low noise. However, when they have knowledge of the related factors, especially radiation exposure, they can contribute to the optimization process.

This takes us to the root of one of the major issues in applied clinical physics and the expanding role of medical physicists. That is the transition from *equipment performance* in the context of quality assurance and control activities to *procedure optimization* in clinical applications.

## VIII. THE MEDICAL PHYSICIST AND CLINICAL PROCEDURE OPTIMIZATION

The formation of medical images in a digital format brings advantages and values but also adds complexity to the imaging process. This is because of the digital elements with sizes that vary over a large range (0.05mm – 5.0mm) which impact two generally opposing image quality characteristics (blur and noise) along with other conflicting factors including radiation dose to patients and image acquisition time in some procedures, including MRI and radionuclide imaging. It is this complexity and added physics issues associated with the digital process that requires knowledgeable and experienced medical physicists as active members of the clinical imaging team as illustrated in Figure 10.

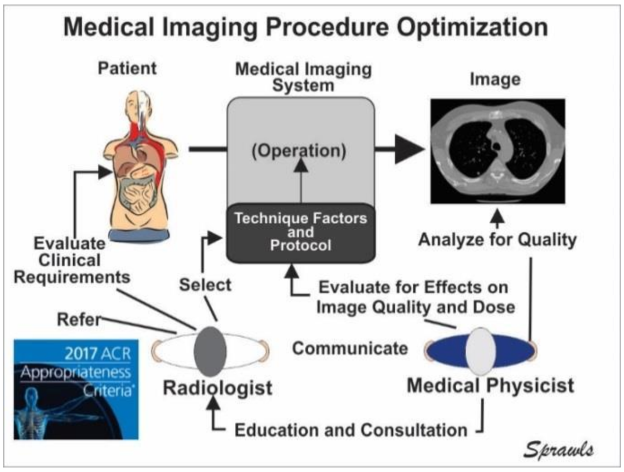


Figure 10. The role of the medical physicist in obtaining clinical images that is optimized with respect to quality and risk to patients.

A first step for the medical physics profession is to enhance educational programs, including degree granting, residency, and continuing education, to include comprehensive coverage of the digital process, its impact on image quality and related factors, along with knowledge of the imaging methods and procedures as they relate to the anatomy, physiology, and pathological conditions within the human body, as now required for medical physics certification by the American Board of Radiology (ABR). Providing some of the educational topics specific to the structure of digital images is one of the objectives of this article. It is this knowledge that enables the medical physicist to become an active member of the clinical medical imaging team with the ultimate effect of providing optimized medical imaging procedures with respect to image quality and risk management. As illustrated in Figure 9 this involves two major functions with respect to other members of the clinical team--education and consultation. As clinical medical physicists we are not the members of the staff who select and adjust the imaging methods and procedures for each individual patient. That is the responsibility of the radiologists and imaging technologists. However, especially because of the complexity of the physics relating to the digital imaging process it is the physicist who has the knowledge that is required for obtaining optimum imaging outcomes. The greatest impact medical physicists can have is by providing education for the other medical imaging professionals.

Educational resources that can be used for that purpose are available at:

http://www.sprawls.org/resources/DIGITAL/

## IX. SUMMARY AND CONCLUSIONS

With images from all methods and modalities now in digital form there are factors in addition to characteristics of the radiation that must be considered in adjusting imaging procedures that are optimized for a specific clinical procedure. The digital element (voxel and pixel) size is a critical factor in this process. Because of the multiple and conflicting effects of element size on image quality and factors including radiation dose to patients, medical physics educational programs need to be enhanced to provide this knowledge for both medical physicists, working as educators and consultants, and radiologists who have responsibility for individual clinical procedures. This is the expanding opportunity for medical physicists.

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