Image Postprocessing in Digital Radiology—A Primer for Technologists

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LEARNING OBJECTIVES

On completion of this directed reading article, readers should be able to:

1. Define the term "digital image processing"
2. State the motivation for developing digital imaging modalities such as computed radiography (CR) and computed tomography (CT)
3. Describe the rationale for understanding the use of image postprocessing techniques in digital radiology
4. List examples of image postprocessing techniques currently used in digital imaging modalities
5. Briefly explain the meaning of the term "image domain" and identify the most conspicuous difference between the spatial location domain and the spatial frequency domain
6. Describe the characteristics of a digital image
7. Identify and briefly describe five classes of image postprocessing operations as stated by author Baxes
8. State the major difference between point, local, and global processing algorithms
9. Explain each of the following:

   ○ Histogram
   ○ Look-up table
   ○ Windowing
   ○ Window width
   ○ Window level
10. Explain the characteristics of spatial frequency filtering using high-pass and low-pass filters
11. Describe the basic features of the commercial image processing tool Photoshop and explain how it can be used in medical imaging
12. Define the term "compression ratio"
13. Distinguish between reversible (lossless) compression and irreversible (lossy) compression
14. State the problems and advantages of irreversible compression for use in digital imaging

*This article is a directed reading and provides the equivalent of 2 hours of continuing education that may be applied to your provincial credit system.

ABSTRACT

This article deals with several image postprocessing concepts that are now commonplace in digital imaging in medicine. First, the motivation for the development of digital imaging modalities is described, followed by a rationale for understanding image postprocessing operations that have become common in radiology.

Second, the image domain concept is outlined with a focus on the characteristics of a spatial location domain image including the matrix, pixels, and the bit depth. In addition, the transformation of the spatial location domain image into the spatial frequency domain is described.

The third topic addresses five classes of image processing algorithms including image restoration, image analysis, image synthesis, image enhancement, and image compression.

The article continues with a detailed description of point processing operations as well as local processing operations. The former is discussed in terms of the histogram, look-up table (LUT), and windowing. The latter describes spatial location filtering (convolution) and spatial frequency filtering using high- and low-pass digital filters, followed by a brief description of the unsharp masking technique.

The fifth major topic presents essential features of the commercially available image postprocessing tool Photoshop, with applications in medical imaging and an emphasis on how this tool can be used by teachers and students alike in an educational environment.

Finally, a technical overview of image compression is reviewed with a discussion of compression ratio and types of image compression techniques. In particular, irreversible compression is outlined briefly, and its effect on the visual quality of images is demonstrated.

Furthermore, a statement from the Canadian Association of Radiologists (CAR) on the use of irreversible compression in digital radiology is provided. The article concludes with a summary of image postprocessing as an essential tool for those who work in a digital imaging environment.

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Introduction

Image postprocessing belongs to the domain of digital image processing, which is simply the processing of images using a digital computer. Film-based radiology is now obsolete and has evolved into various digital imaging modalities, including computed radiography, flat-panel digital radiography, digital fluoroscopy, digital mammography, computed tomography (CT), magnetic resonance imaging (MRI), nuclear medicine, and diagnostic medical sonography. Thus, digital image processing in radiology has become one of the routine skills of technologists and radiologists alike. In addition, the use of the CT and MRI scanners has become an integral imaging component in radiation treatment planning. Therefore, it is important that technologists understand the nature and scope not only of digital images but also of digital image processing, to become effective and efficient users of the new technologies that have made a significant impact on the care and management of patients.

The major goal of digital image postprocessing in medical imaging is to alter or change an image to enhance diagnostic interpretation. For example, images can be postprocessed for the purpose of image enhancement, image restoration, image analysis, and image compression. These operations are intended to transform an input image into an output image to suit the viewing needs of the observer in making a diagnosis. In addition, these operations can also be used in digital photography and have become available in commercial image processing software. One such popular software package is Adobe Photoshop (Adobe Systems Inc, San Jose, CA). This software is a powerful tool that can be used to illustrate image postprocessing to students studying digital imaging technologies.

The purpose of this directed reading is to outline the major characteristics of digital image postprocessing as it relates to digital imaging systems used in radiology. First the limitations of film-based imaging will be described; and, second, digital image postprocessing operations that are commonly used in digital imaging modalities will be discussed. Third, the essential features of Photoshop will be highlighted for the purpose of illustrating selected features of this tool and how it can be used for teaching and learning. Fourth, a technical overview of image compression and its importance in digital imaging will be presented.

Motivation for Developing Digital Imaging Modalities

Film-based imaging, or film-screen radiography, as it is often referred to, has been used routinely ever since the discovery of x-rays in 1895. A radiographic image is created using a number of steps. First, the patient is exposed to a predetermined amount of radiation to provide the required diagnostic image quality. The latent image formed on the film is rendered visible through chemical processing. The processed image is a hard-copy film image with a fixed optical density, used by the radiologist to make a diagnosis of the patient's medical condition.

Problems in obtaining the optimum image are often a challenge in film-screen radiography. If the radiation exposure is too high, the film is overexposed and the processed image appears

too dark. Alternatively, if the radiation exposure is too low, the processed image appears too light and cannot be used to make a diagnosis. Specifically, these images lack the proper image density and contrast, and would have to be repeated in an effort to obtain acceptable image quality needed to make a diagnosis. In this situation, the patient receives an increase in the radiation dose [1].

There are additional shortcomings associated with film-screen radiography. The film-screen image receptor is not the ideal medium to perform the functions of radiation detection, image display, and image archiving. As a radiation detector, film-screen cannot show differences in tissue contrast that are less than 10%. This means that contrast resolution is limited. However, film-screen radiography offers the best spatial resolution compared to any other imaging modality such as CT, MRI, or nuclear medicine, and this is one of the main reasons why radiography has played a significant role in imaging patients [1].

As a display medium, the optical range and contrast for film image are fixed and limited. Film can only display once, and the optical range and contrast are determined by the exposure technique factors used to produce the image. To change the image display (optical range and contrast), one has to repeat the exposure using a different set of technical factors (mAs and kVp), thus increasing the dose to the patient [1]. As an archive medium, film is usually stored in envelopes and housed in a large room. It requires manual handling for archiving and physical retrieval by an individual.

These limitations provide the motivation for developing digital imaging systems for use in digital radiology because of their potential for image postprocessing, which can overcome these problems.

Historical Perspectives

Digital image processing underwent significant developments at the Jet Propulsion Laboratory at the California Institute of Technology (Caltech) and was subsequently used by the National Aeronautics and Space Administration (NASA) in a wide range of space exploration applications. The history of digital image processing dates back several decades when NASA was working on its lunar and planetary exploration programs. For example, the organization used computers to process images beamed back from the Ranger spacecraft to improve the visualization of details of the moon's surface. Later, the benefits

gained from NASA's space program were applied in several other fields such as biology, defense, forensics, photography, remote sensing, and medical imaging, to mention only a few [2,3].

Today, digital photography is commonplace, and several types of image postprocessing software are now available commercially for users to become actively engaged in enhancing their photographs [4]. One such software is Adobe Photoshop Essential, the features of which will be highlighted in this paper.

Rationale for Understanding Digital Image Postprocessing in Radiology

Why is it important for technologists to understand the nature and scope of digital image postprocessing? The answer will become clear in this section of the directed reading. First, it is important to understand the components of a typical digital imaging system, and then to appreciate the different types of specific image postprocessing operations used in the various imaging modalities.

Components of a Digital Imaging System

The major components of a generic digital imaging system for use in radiology are shown in Figure 1. The essential components include data acquisition, image processing, image display/storage/archiving, and picture archiving and communication systems (PACS).

It is not within the scope of this article to describe these components in any detail; however, the following points are in order:

○ In data acquisition, raw digital data are collected from the patient.
○ The raw digital data are processed by a digital computer for subsequent image display to a human observer. Such processing is referred to as digital image processing.
○ Digital image processing is divided into two parts: preprocessing and postprocessing. While preprocessing operations apply appropriate corrections to the raw data, postprocessing is intended to change the image contrast, reduce image noise and enhance the sharpness of the image displayed in an effort to enhance diagnostic interpretation. This paper will focus on image postprocessing operations and techniques.
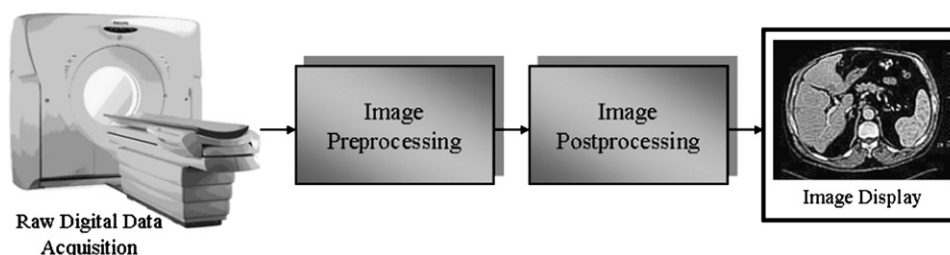

Figure 1. **Major Components of a Digital Imaging System**. Image processing consists of preprocessing, in which corrections are made to the raw data, and postprocessing, in which displayed images can be manipulated for the purpose of enhancing diagnostic interpretation capability.

In radiology, digital image acquisition systems include the following: computed tomography (CT), computed radiography (CR), digital radiography (DR), digital mammography (DM), and digital fluoroscopy (DF) for both routine gastrointestinal fluoroscopy and vascular imaging; and magnetic resonance imaging (MRI), nuclear medicine, and medical sonography. These technologies are described in detail by Brennan et al [5]. Furthermore, CT and MRI scanners are now integral imaging equipment in radiation oncology [6,7]. All of these digital imaging systems use digital image postprocessing operations to alter the displayed digital image, with the goal of enhancing diagnosis.

Specific Image Postprocessing Operations

Common image processing operations in CT include those for image reformatting, windowing, region of interest (ROI), magnification, shaded surface display, volume rendering, profile, histogram, and collage [7].

In CR and DR, image postprocessing includes gray scale processing (windowing), spatial filtering, and dynamic range control.

In digital subtracting angiography or digital fluoroscopy, common image postprocessing operations include analytic processing, subtraction of images out of a sequence, gray scale processing, temporal frame averaging, edge enhancement, and pixel shifting [8].

In digital mammography, image postprocessing techniques include manual intensity windowing, histogram-based intensity windowing, mixture model intensity windowing, contrast-limited adaptive histogram equalization, unsharp masking, peripheral equalization, and text processing [9]. These are described in detail by Pisano et al [10].

In radiation oncology, image postprocessing operations include all those mentioned for CT, as well as segmentation, which includes classification, edge detection, boundary tracking, geodesic active contours, extraction of tubular objects, atlas registration, and interactive segmentation [6]. All concepts mentioned above will be briefly explained in this reading.

The Image Domain Concept

To appreciate image postprocessing operations, it is essential to have a firm grasp of what is meant by the term "image domain". Images can be represented in two domains, based on how they are acquired [11]. These domains include the *spatial location domain*, and the *spatial frequency domain*. All images displayed for viewing are in the spatial location domain. Radiography and CT, for example, acquire images in the spatial location domain. MRI acquires images in the spatial frequency domain; and, in this case, these images must be converted into the spatial location domain for viewing by technologists and the radiologist. Medical physicists, however, appreciate the spatial frequency domain images and can use them to determine and assess physical characteristics of the imaging system.

A spatial location domain digital image is a numeric image described as a matrix of pixels. Apart from being a numeric image, there are other elements of a digital image that are important to our understanding of digital image processing. A digital image is made up of a 2-dimensional array of numbers called a *matrix.* The matrix consists of columns (M) and rows (N) that define small square regions called *picture elements* or *pixels,* as illustrated in Figure 2. The dimensions of the image can be described by M, N, and the relationship $M \times N \times k$ *bits* give the size of the image. The spatial location 10, 16 will describe a pixel that is located 10 pixels to the right of the left-hand side (L) of the image and 16 lines down from the top of the image. The pixel value in this digital image is 144 (Figure 2).

In the relationship $M \times N \times k$ *bits*, the term *k bits* implies that every pixel in the digital image matrix $M \times N$ is represented by k binary digits. The number of bits per pixel is the bit depth. Because the binary number system uses the base 2, k bits = 2^k; therefore, each pixel will have 2^k gray levels. For example, in a digital image with a bit depth of 2, each pixel will have 2^2 (4) gray levels (density). Similarly, a bit depth of 8 implies that each pixel will have 2^8 (256) gray levels or shades of gray. The effect of matrix size and bit depth on the spatial resolution and density resolution, respectively, are clearly seen in Figure 3. In addition, the pixel size can be calculated using the algebraic expression: *pixel size = field of view (FOV)/ matrix size.*

Typical matrix sizes and bit depths for nuclear medicine, MRI, CT, DSA, CR, DR and digital mammography are $128 \times 128 \times 12$; $256 \times 256 \times 12$; $512 \times 512 \times 12$; $1024 \times 1024 \times 10$; $2048 \times 2048 \times 12$; $2048 \times 2048 \times 12$; and $4096 \times 4096 \times 12$, respectively.

Images can also be acquired in the spatial frequency domain, such as those acquired in MRI. The term *frequency* refers to the number of cycles per unit length: that is, the number of times a signal changes per unit length. Whereas small structures
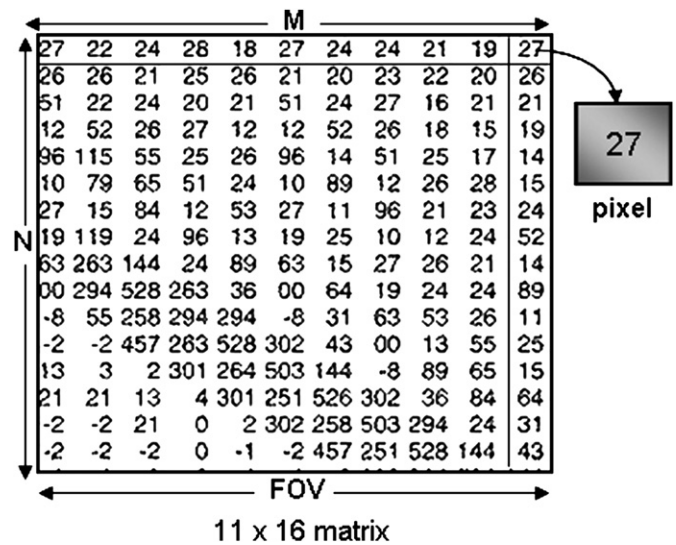

Figure 2. **Digital Image Format**. The format of a digital image includes columns (M) and rows (N) that define small, square regions called picture elements, or pixels. The field-of-view (FOV) is one dimension of the matrix and is used to calculate the size of the pixel. A right-handed coordinate system is used to describe digital images in the spatial location domain. See text for further explanation.
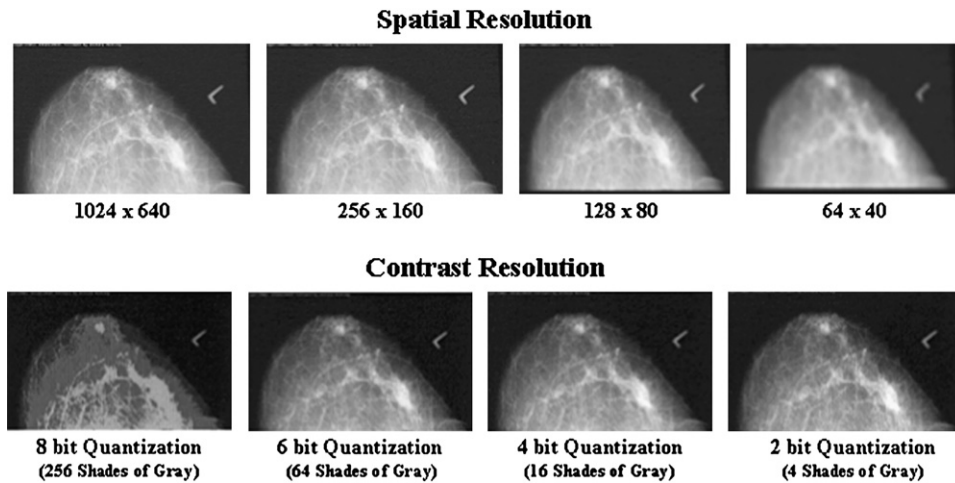
Spatial Resolution

| 1024 x 640 | 256 x 160 | 128 x 80 | 64 x 40 |

Contrast Resolution

| 8 bit Quantization (256 Shades of Gray) | 6 bit Quantization (64 Shades of Gray) | 4 bit Quantization (16 Shades of Gray) | 2 bit Quantization (4 Shades of Gray) |

Figure 3. **Effects of Matrix Sizes and Bit Depths**. Visual effect of different matrix sizes and bit depths on spatial and contrast resolution of an image, respectively. (Reprinted with permission from Bruno Jaggi, PEng–Biomedical Engineering, British Columbia Institute of Technology.)

within an object (patient) produce high frequencies that represent detail in the image, large structures produce low frequencies that represent contrast information in the image.

Digital image processing can transform one image domain into another image domain. For example, an image in the spatial location domain can be transformed into a spatial frequency domain image, as illustrated in Figure 4. The Fourier transform (FT) is used to perform this task. The FT is mathematically rigorous and will not be covered in this article. The FT converts a function in the time domain (say, signal intensity versus time) to a function in frequency domain (say, signal intensity versus frequency). The inverse FT denoted by FT^{-1} is used to transform an image in the frequency domain back to the spatial location domain (Figure 4) for viewing by radiologists and technologists. Physicists and engineers, on the other hand, would probably prefer to view images in the frequency domain.
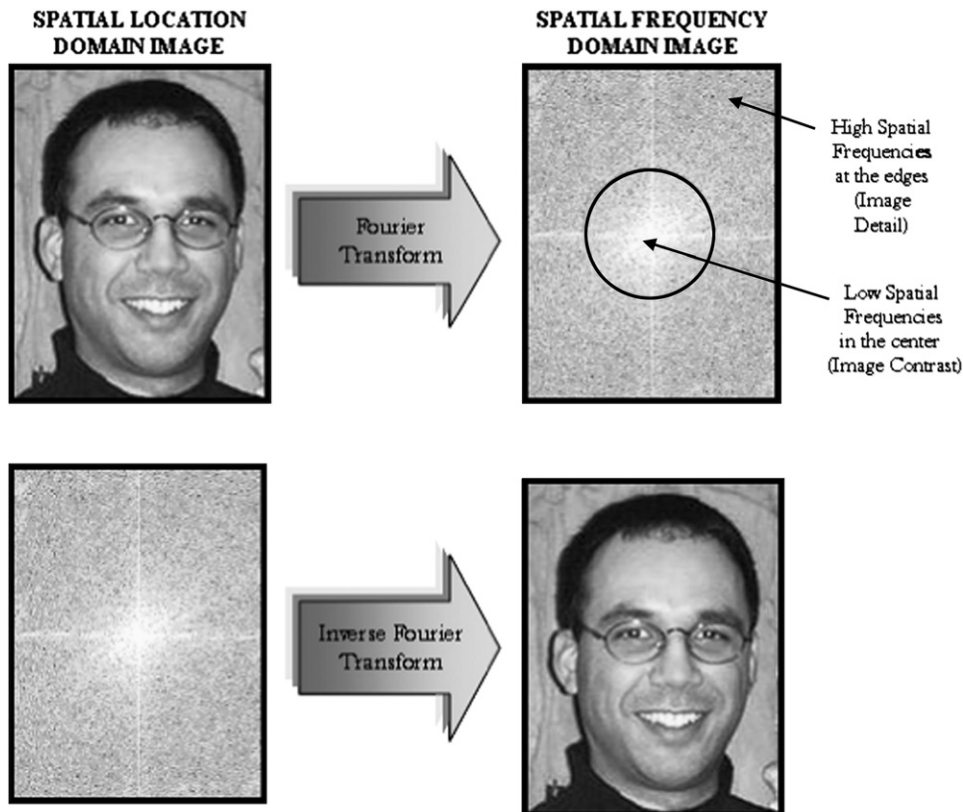

Figure 4. **Fourier Transform**. The Fourier transform (FT) is used to convert an image in the spatial location domain into an image in the spatial frequency domain for processing by a computer. The inverse FT (FT^{-1}) is used to convert the spatial frequency domain image back into a spatial location image for viewing by human observers.

Spatial frequencies can be used to alter the appearance of images by using high- or low-spatial frequency filters to enhance or suppress certain features of the image. For example, an image can be sharpened or blurred by using high- and low-pass filters, respectively [11]. This will be described later in this paper.

Classes of Image Postprocessing

There are several operations used in digital image processing to transform an input image into an output image to suit the needs of the observer. Baxes [2] and Gonzalez [3] identify at least five fundamental classes of operations (Figure 5), including image enhancement, image restoration, image analysis, image compression and image synthesis. Although it is not within the scope of this paper to describe all of these in any great detail, it is noteworthy to mention the purpose of each class and state their particular operations. As image enhancement and image compression are most commonly used by technologists and radiologists, these will be described in more detail later in this paper. For a more complete and thorough description of these classes, readers are referred to the work of Baxes [2] and Gonzalez [3].

1. **Image restoration:** The purpose of image restoration is to improve the quality of images that have distortions or degradations. Image restoration is commonplace in spacecraft imagery. Images sent to Earth from various camera systems on spacecrafts are subject to distortions or degradations that must be corrected for proper viewing. Blurred images, for example, can be filtered to make them sharper.

2. **Image analysis:** This class of digital image processing allows measurements and statistics to be performed as well as image segmentation, feature extraction, and classification of objects. Baxes states that "the process of analyzing objects in an image begins with image segmentation operations, such as image enhancement or restoration operations. These operations are used to isolate and highlight the objects of interest. Then the features of the objects are extracted resulting in object outlines or other object measures. These measures describe and characterize the objects in the image. Finally, the object measures are used to classify the objects into specific categories [2]." Segmentation operations are used in 3D medical imaging [6,7].

3. **Image synthesis:** These processing operations "create images from other images or nonimage data. These operations are used when a desired image is either physically impossible or impractical to acquire, or does not exist in a physical form at all [3]." Examples of these operations are image reconstruction techniques, which are the basis for the production of CT and MR images, as well as 3D visualization techniques [6], which are based on computer graphics technology.

4. **Image enhancement:** The purpose of this class of processing is to generate an image that is more pleasing to the observer. Certain characteristics such as contours and shapes can be enhanced to improve the overall quality of the image. The operations include contrast enhancement, edge enhancement, spatial and frequency filtering, image combining, and noise reduction.

5. **Image compression:** The purpose of image compression of digital images is to reduce the size of the image to decrease transmission time and to reduce storage space. In general, there are two forms of image compression, lossy, and lossless compression. In lossless compression there is no loss of any information in the image (detail is not compromised) when the image is decompressed. In lossy compression, there is some loss of image details when the image is decompressed. The latter has specific uses, especially in situations when it is not necessary to have exact details of the original image.

This paper will address only details of image enhancement and image compression, as these are the most popular image postprocessing operations used in medical imaging technologies.
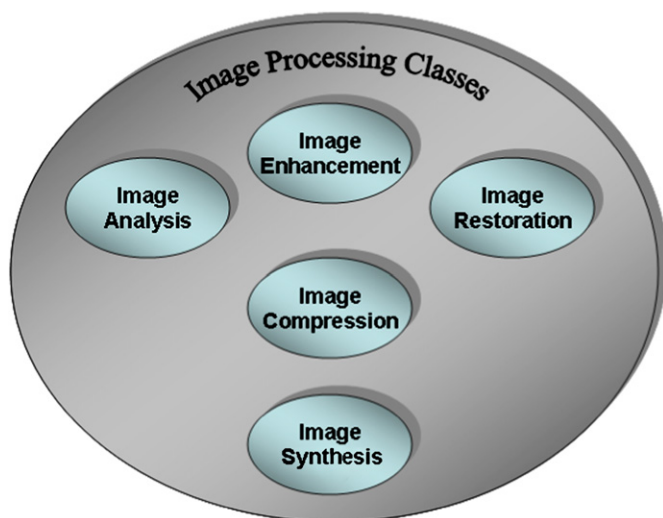

Figure 5. **Classes of Image Processing Operations.** The 5 fundamental classes of image processing operations according to image processing experts Gonzalez [3] and Baxes [2]. See text for further descriptions of each of these.

Image Postprocessing Operations: A Conceptual Overview

Both past and current-day image postprocessing technology includes a wide range of image processing algorithms for use in digital radiology [3,7–11]. These include *point processing operations* such as gray scale processing (windowing, image subtraction, and temporal averaging); *local processing operations* (such as spatial filtering, edge enhancement, and smoothing); and *global operations* such as the Fourier transform (FT). It is not within the scope of this article to describe the details of these processing algorithms; however, a conceptual overview of point and local operations for single images (as opposed to multiple images) will be presented, since a number of them are used in digital radiology.

Image processing operations are intended to change the intensity values of the pixels in the input image, and to display the resulting changes in the output image with the goal of changing the characteristics of the image to suit the needs of the observer to enhance diagnosis. This paper will outline the elements of those operations that are specifically intended to change and optimize image contrast, improve image detail by

sharpening the image, and decrease the noise present in the image.

Point Processing Operations

These operations are simple, and are most frequently used in digital diagnostic imaging. The conceptual framework for this operation is illustrated in Figure 6. The value of one (point) input image pixel is mapped onto the corresponding output image pixel; that is, the output image pixel value at the same location as on the input image matrix depends on the value of the input image pixel. The operation (algorithm) allows the entire input image matrix to be scanned pixel-by-pixel, using a "pixel point process [2,3]" until the entire image is transformed.

One common point processing operation is referred to as gray-level mapping or gray scale processing. Other terms that are used to describe gray-level mapping are *contrast stretching*, *contrast enhancement*, *histogram modification*, *histogram stretching*, or simply *windowing*. Windowing is the most commonly used image processing operation in digital diagnostic imaging, including computed radiography, digital radiography using flat-panel detectors, CT, and MRI.

Image contrast and brightness transformations require an understanding of two basic concepts, the look-up-table (LUT) and the windowing. However, before these can be understood, the concept of a histogram must be described.

The Histogram

The histogram is an essential tool in image postprocessing, because it can be used to alter image brightness and contrast dramatically. An image histogram is a graph of the number of pixels in the entire image, or part of the image having the same gray levels (density values) plotted as a function of the gray levels, as shown in Figure 7. If the histogram is modified, the brightness and contrast of the image will change as well. This operation is called *histogram modification* or *histogram stretching*. If the values of the histogram are concentrated in the lower end of the range of values, the image appears dark. For a bright image, the values are weighted toward the higher end of the range of values. The effect of this will be shown later in the article using Photoshop for a photographic image rather than a medical image, since the effect is more dramatic.
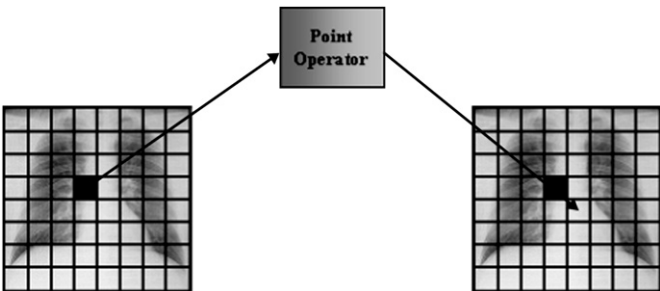
Figure 7. **The Histogram**. Graph of the number of pixels in the entire image having the same gray levels (density values), plotted as a function of the gray levels, is referred to as a histogram. See text for further explanation. © 2004, the American Society of Radiologic Technologists. All rights reserved. Reprinted with permission of the ASRT.

The Look-Up Table

To illustrate the concept of a LUT, two examples will be highlighted: a numeric example and a graphic example. Sprawls [12] provides us with two excellent examples, and they will be described here to illustrate the concept of a LUT. First consider Figure 8, which shows a low-contrast numeric image with a contrast difference (that is, the object relative to the background) of 10 (40-30), where 40 represents the background contrast and 30 represents the object contrast. "The LUT is then used to change the low-contrast numeric image to a high-contrast image by assigning numbers to the input values 40 and 30 that will subsequently change them into 90 and 10, respectively. The contrast difference for the new output image (on the right) is now 80 (90-10), and therefore this image appears as a high-contrast image. During digital image processing, the LUT determines the numbers assigned to the input pixel values that change them into output pixel values that result in a change in contrast and brightness of the image [1]."

On the other hand, consider Figure 9A, which shows a plot of the input image pixel values as a function of the output image pixel values. In this case the values are the same. "For example, the value 1024 for the input image matches the value 1024 for

Figure 6. **Conceptual Framework for a Point Processing Operation**. As can be seen, one (point) input image pixel is mapped onto the corresponding output image pixel. The output image pixel value is located at the same location as on the input image matrix depending on the value of the input image pixel.
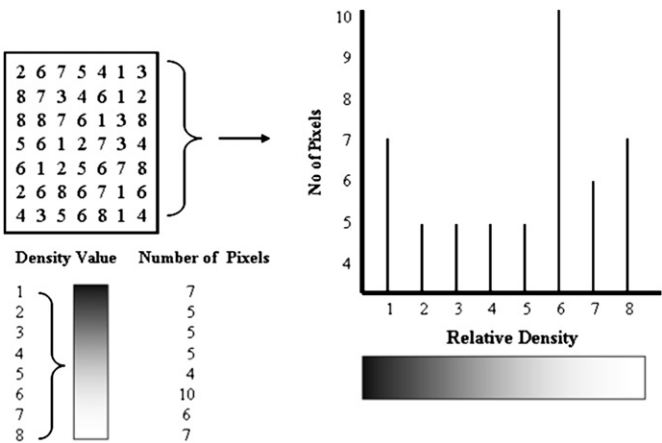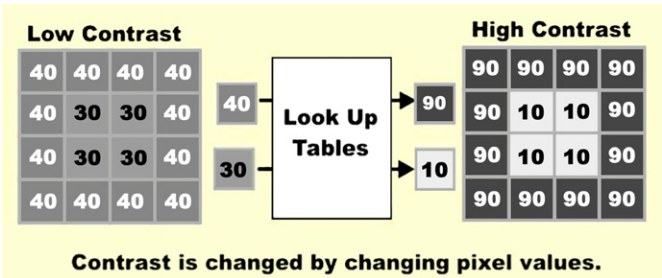
Figure 8. **The Look-Up-Table—Numeric**. Numerical example of the concept of a look-up table (LUT); see text for further explanation. (Reprinted with permission from Perry Sprawls, PhD, Emory University, Atlanta, GA.)
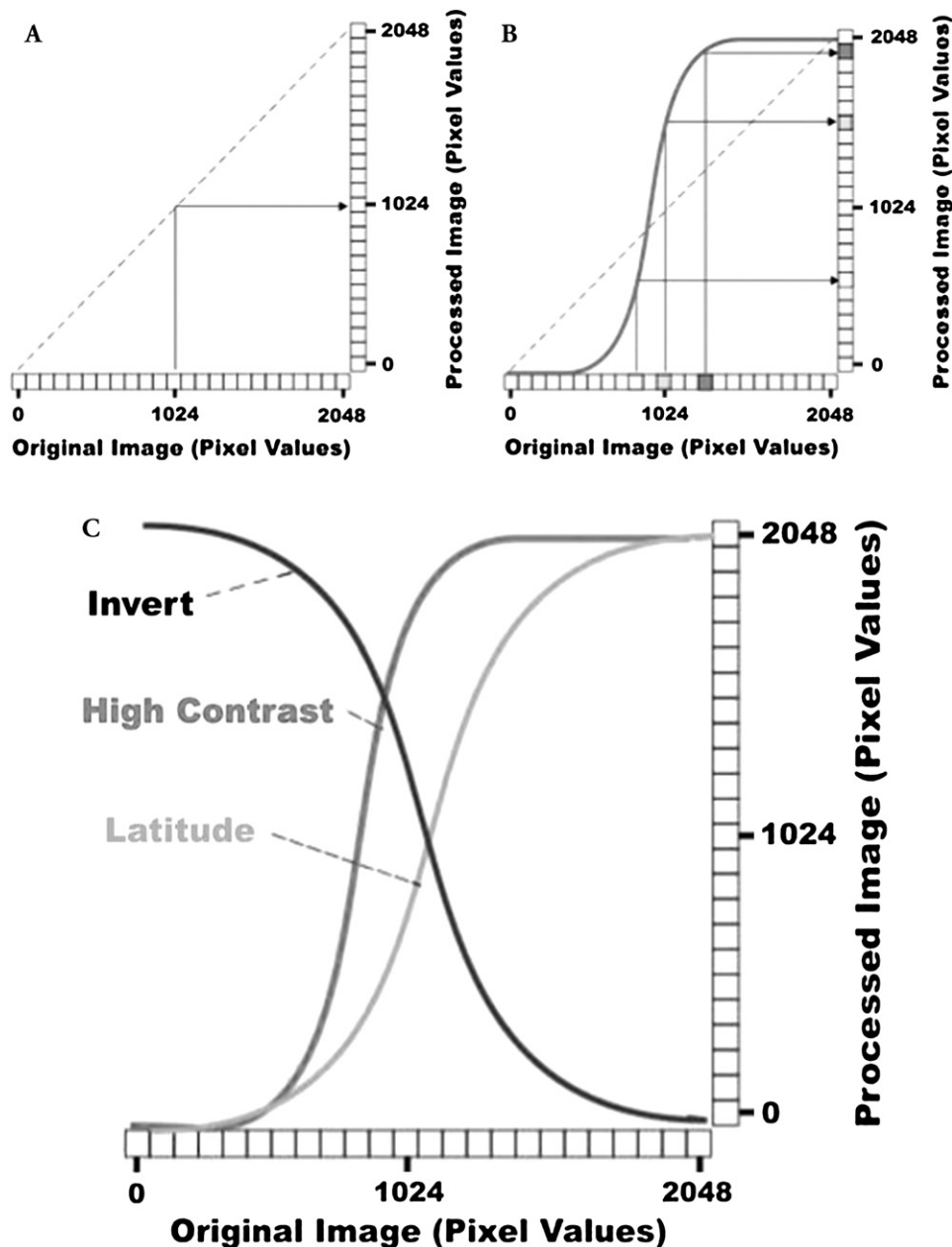
Figure 9. **The Look-Up Table–Graphic**. Graphic example of the look-up table (LUT) concept. See text for further explanation. (Reprinted with permission from Perry Sprawls, PhD, Emory University, Atlanta, GA.)

the output image. The resulting graph is a straight line. Are LUT curves possible? The answer is yes, as is clearly apparent in Figure 9B. This is the classic characteristic curve (H and D curve) for film. Finally, in Figure 9C, 3 LUT curves are shown: a latitude curve, a high contrast curve and an invert curve. Recall, that the slope of the characteristic curve influences the contrast of the image. A steep slope results in a high contrast image while a less steep slope (<45°) will result in decreased contrast [1]."

Both CR and DR systems make use of a wide range of LUTs stored in the system for the different types of clinical examinations (eg, chest, spine, pelvis, and extremities). This means that the operator should select the appropriate LUT to match the part being imaged when using these systems. An important

point to note here is the following: since digital radiographic detectors have wide exposure latitude and a linear response, the image displayed without processing appears as a low-contrast image. A processing example for a chest image using the LUT is shown in Figure 10. The low-contrast image is seen on the left side of the figure, whereas the high-contrast image is illustrated on the right side.

The Concept of Windowing

Windowing is one of the most popular image postprocessing operations used by both technologists and radiologists alike to change the contrast and brightness of an image [7]. A digital image
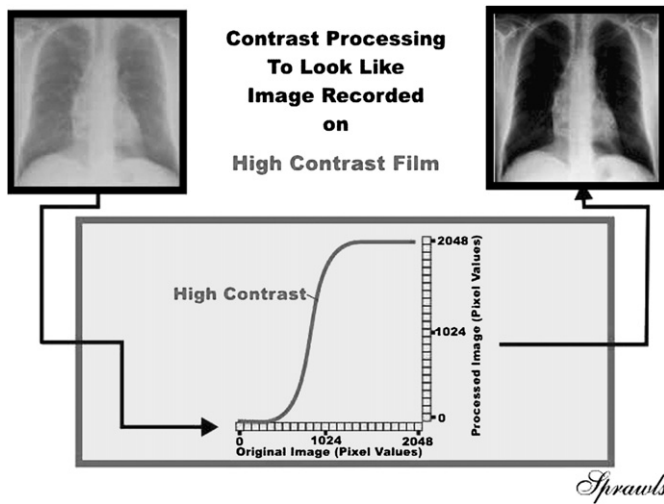
Figure 10. **The Look-Up Table in Postprocessing**. Example of use of the look-up table (LUT) in postprocessing of a chest image. (Reprinted with permission from Perry Sprawls, PhD, Emory University, Atlanta, GA.)

is made up of a range of numbers. By definition, the range of the numbers in the image is the window width (WW), and the center of the range is defined as the window level (WL) as illustrated in Figure 11. While the range of the pixel values (gray levels) is 2000
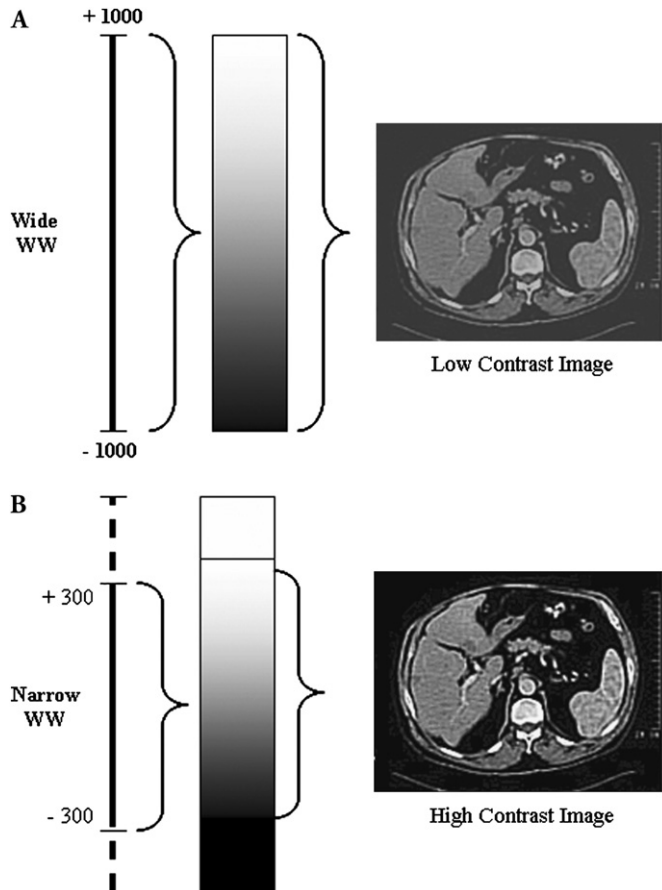
(1000 + 1000), the WL is 0. In addition, the displayed image contrast range (bar graph) is also shown.

While the WW controls image contrast, the WL controls the brightness of the image. In an image, the displayed gray levels will range from −1/2WW+WL to +1/2WW+WL. The displayed WW and WL values are always shown on the image. While narrow WW provides improved image contrast, a wide WW will show an image with less contrast. This effect is shown in Figure 12. On the other hand, when the WL is increased, the image becomes darker since more of the lower numbers will be displayed as is shown in Figure 13.

It is interesting to note that image subtraction and temporal averaging are also classified as point processing operations. These are used routinely in digital subtraction angiography. Essentially, in image subtraction the pixel values from post-contrast images are subtracted from pixel values from the first pre-contrast image (mask) to show contrast-filled blood vessels, with the other structures removed to enhance the diagnostic impressions of the radiologist. Temporal averaging, on the other hand, refers to subtraction of images in time. In particular, temporal averaging involves averaging a set of images with the ultimate goal of reducing image noise. The greater the number of images averaged, the less the image noise. Interested readers may refer to Pooley et al [8] for further details of these two techniques.
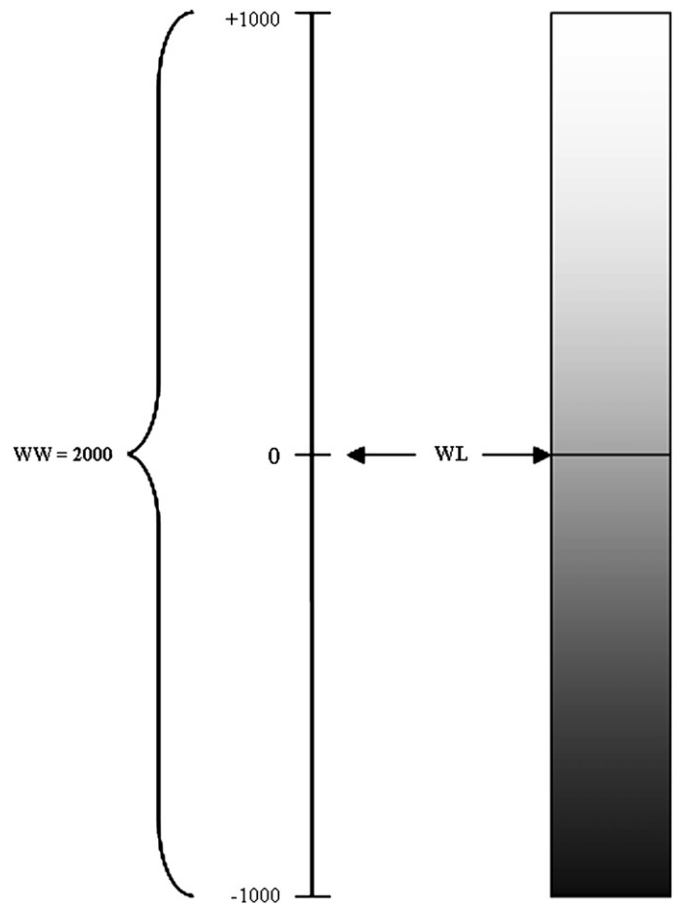

Figure 11. **Window Width and Window Level**. Graphic illustration of the definitions of the image postprocessing concepts of window width (WW) and the window level (WL).

Figure 12. **Effect of Window Width**. Visual effect of the window width (WW) on the contrast of an image, with window level (WL) held constant.
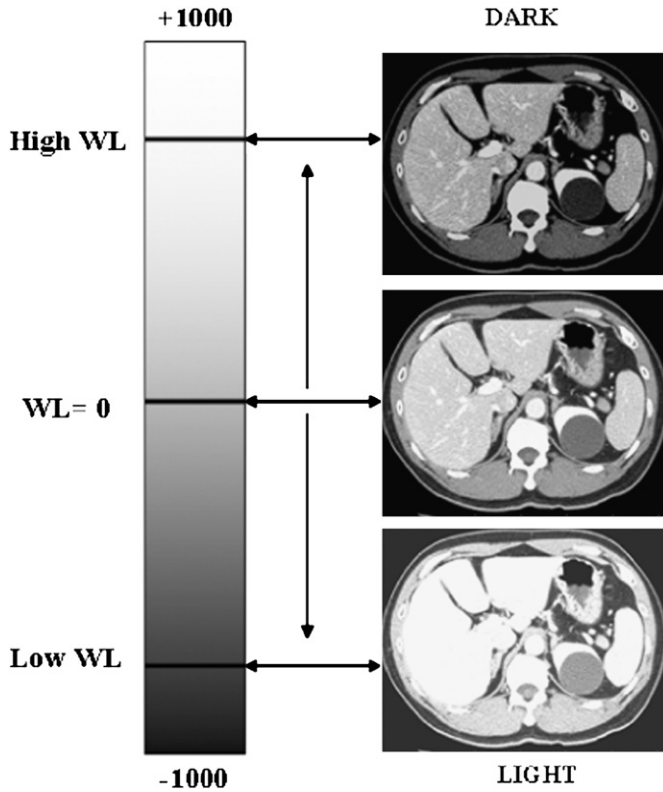
Figure 13. **Effect of Window Level**. Visual effect of the window level (WL) on the brightness of an image, with window width (WW) held constant.

Local Processing Operations

A local processing operation is illustrated in Figure 14. As can be seen, it is an operation in which the output image pixel value is obtained from a small area of pixels around the corresponding input image pixel. A notable example is that of spatial frequency filtering, to be described later.

An image in the spatial location domain can be transformed into an image in the spatial frequency domain. The spatial frequency domain image would be made of high spatial frequencies that represent detail, and low spatial frequencies, which represent contrast information in the image. The idea of using spatial frequency filtering (processing) is to use the high and low frequencies to change the characteristics of the image to suit the needs of the observer to enhance diagnosis. For example spatial frequency processing can sharpen, smooth, or blur images, as
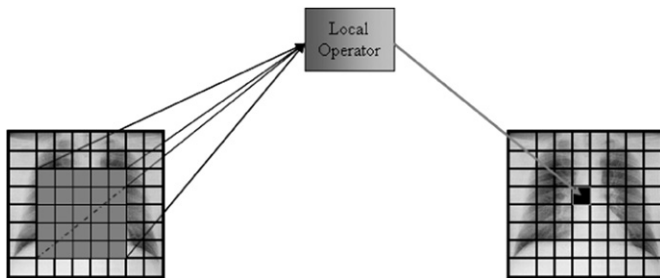

Figure 14. **Local Processing**. A local processing operation is one in which the output image pixel value is obtained from a small area of pixels around the corresponding input pixel. See text for further explanation.
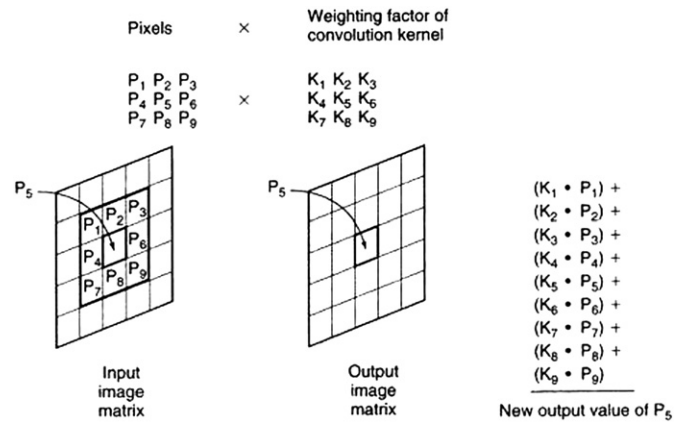

Figure 15. **Convolution Technique**. The image postprocessing operation of digital filtering in the spatial location domain, known as the convolution technique.

well as reduce the noise in the image and extract certain features from the image. Spatial frequency filtering can be done in the frequency domain, or it can be done in the spatial location domain. Whereas the former uses the FT, the latter makes use of the pixel values themselves.

Spatial Location Filtering: Convolution

A common example of filtering in the spatial location domain is convolution (Figure 15). The algorithm for convolution is such that "the value of the output pixel depends on a group of pixels in the input image that surround the input pixel of interest: in this case P5. The new value for P5 in the output image is calculated by obtaining its weighted average and that of its surrounding pixels. The average is computed using a group of pixels called a *convolution kernel*, in which each pixel in the kernel is a weighting factor, or a *convolution coefficient*. In general, the size of the kernel is a 3 × 3 matrix. Depending on the type of processing, different types of convolution kernels can be used, in which case the weighting factor is different [7]." In the act of processing, the kernel scans across the entire image, pixel by pixel. Every pixel in the input image, the pixels surrounding it, and the kernel are used to calculate the corresponding output pixel value. It can be seen from Figure 15 that each calculation requires 9 multiplications and 9 summations. This arithmetic can take time, so special hardware (array processors) are used to speed up these calculations.

Spatial Frequency Filtering: High-Pass Filtering

The high-pass filtering process, also known as *edge enhancement* or *sharpness*, is intended to sharpen an input image in the spatial domain that appears blurred. The algorithm is such that first the spatial location image is converted into spatial frequencies using the FT, followed by the use of a high-pass filter that suppresses the low spatial frequencies to produce a sharper output image. This process is shown in Figure 16 for a CT image. The high-pass filter kernel is also shown.

Spatial Frequency Filtering: Low-Pass Filtering

A low-pass filtering process makes use of a low-pass filter to operate on the input image with the goal of smoothing. The
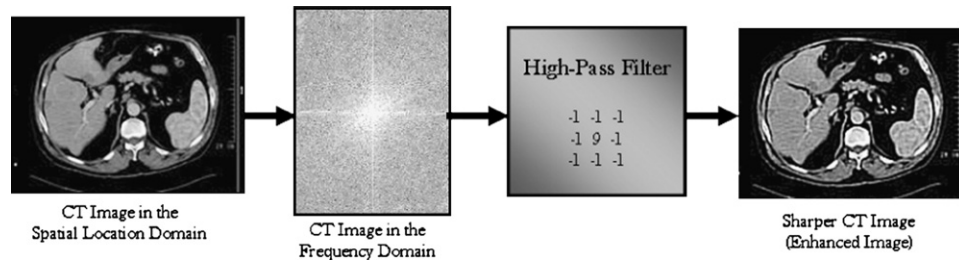
Figure 16. **High-Pass Digital Image Processing Filter**. The effect of a high-pass digital image processing filter on an input image. The output image is much sharper than the input image. This filter suppresses the low spatial frequencies in the image which contains the contrast information.

output image will appear blurred. Smoothing is intended to reduce noise and the displayed brightness levels of pixels; however, image detail is compromised. This is illustrated in Figure 17. The low-pass filter kernel is also shown.

Spatial Frequency Processing: Unsharp Masking

The digital image processing technique of unsharp (ie, blurred) masking uses the blurred image produced from the low-pass filtering process and subtracts it from the original image to produce a sharp image, as illustrated in Figure 18. It can be seen that the output image appears sharper.

Geometric Operations

Another class of image processing operations that are sometimes used in digital radiology is that of geometric operations. These techniques allow the user to change the position or orientation of pixels in the image (Figure 19) rather than the brightness of the pixels. Geometric operations result in the scaling, sizing, rotation, and translation of images, once again, to enhance diagnosis.

Photoshop: A Commercial Photography Image Processing Tool with Applications in Medical Imaging

What is Photoshop?

Photoshop is a digital image processing software suite from Adobe Systems Inc, and is widely considered by the graphic design community to be the industry standard for digital image editing and photography enhancement. Typically used by both expert and novice users, Photoshop offers powerful digital image editing tools such as image filters, histogram manipulation, sharpening/blurring tools, and noise reduction algorithms.

Although Photoshop's most common applications are in commercial and consumer level graphics design and photography editing [4], Photoshop has also been a popular tool among radiologists, technologists, and imaging scientists. With the currently released version of Photoshop CS3 Extended, Adobe has raised the bar even higher by taking on the world of medical imaging with the addition of two new features: Support for DICOM (Digital Imaging and Communications in Medicine) files, and Analysis Tools.

Photoshop and Medical Imaging

The predominant obstacle medical imaging personnel have faced with regards to the use of Photoshop was the lack of support for the most common medical imaging file format, DICOM. As the standard format for receiving medical images, DICOM files most often contain a series of images generated from MRI, ultrasound, or CT scans. Photoshop CS3 Extended now includes new features that apply directly to medical imaging.

When working with DICOM files in Photoshop, the technologist would be presented with a dialog box allowing for a useful choice of options:

- Frame Import: With this option, DICOM frames can be imported onto Photoshop layers, and the choice of an "n-up" configuration display is available to display multiple frames in a user-definable grid format.
- DICOM Dataset: The "Anonymize" option allows one to anonymize patient data, and the "Show Overlays" option allows overlay displays such as image annotations or text.
- Windowing: The user can make adjustments in the contrast and brightness of the frame, either by entering custom
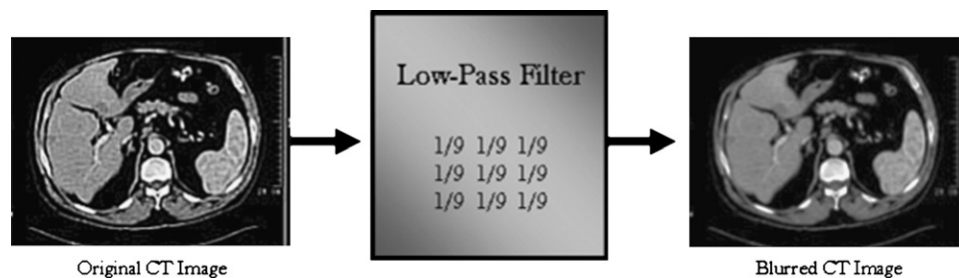

Figure 17. **Low-Pass Digital Image Processing Filter**. The effect of a low-pass digital imaging processing filter. The output image is blurred (smoothing) compared to the input image.
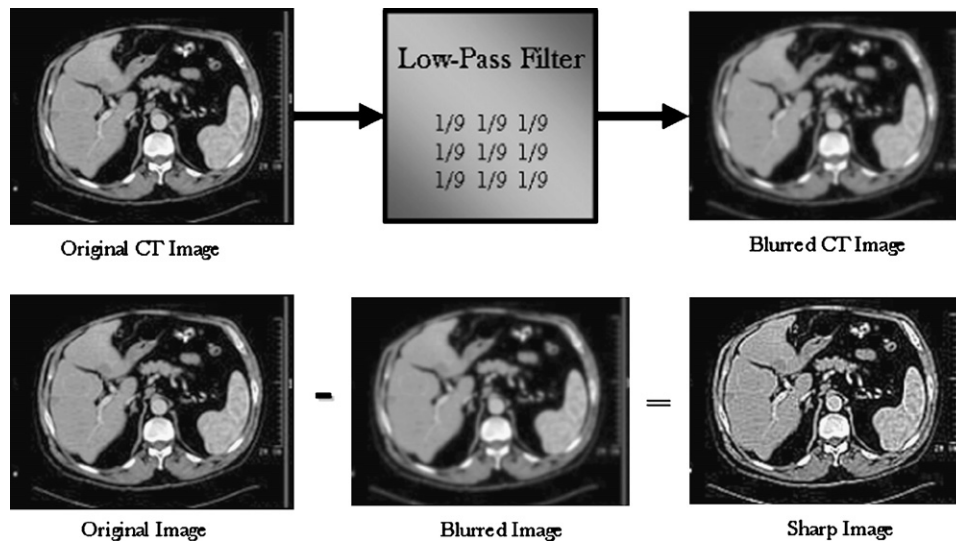
Figure 18. **Unsharp Masking**. The image postprocessing technique of unsharp masking is essentially used to sharpen images. See text for further explanation.

values or by choosing built-in, common radiology presets such as default, lung, bone, or abdomen.

A snapshot of Photoshop's DICOM File Info Dialog is shown below. Once a DICOM file is open, any Photoshop tool is then available to edit, manipulate, or annotate the file. For example, the Pencil tool could be used to circle and highlight an area on the image; the Notes tool could be used to add a comment to the file and sharpening can be performed; and even the Dust and Scratches filter can be used to remove small imperfections in the image. Images can then be resized and saved to any supported file format based on their intended output medium.

Photoshop CS3 Extended offers the medical imaging world a whole new set of analysis and measurement tools for extracting quantitative data on 2-dimensional images. One such tool can be used to define the scale of an image using a known value as a reference point. Once a scale has been defined, the ruler tool (in Photoshop) can be used to measure the pixel length of an area of interest in the image, upon which a logical value can be assigned. For example, if the pixel length of a tumour (in the image) is 50 pixels, a logical value of "5" scale units can be assigned. With this type of scale defined, you can now use the Ruler and Selection tools to measure distances and even areas, recording these measurements into a log, which can also
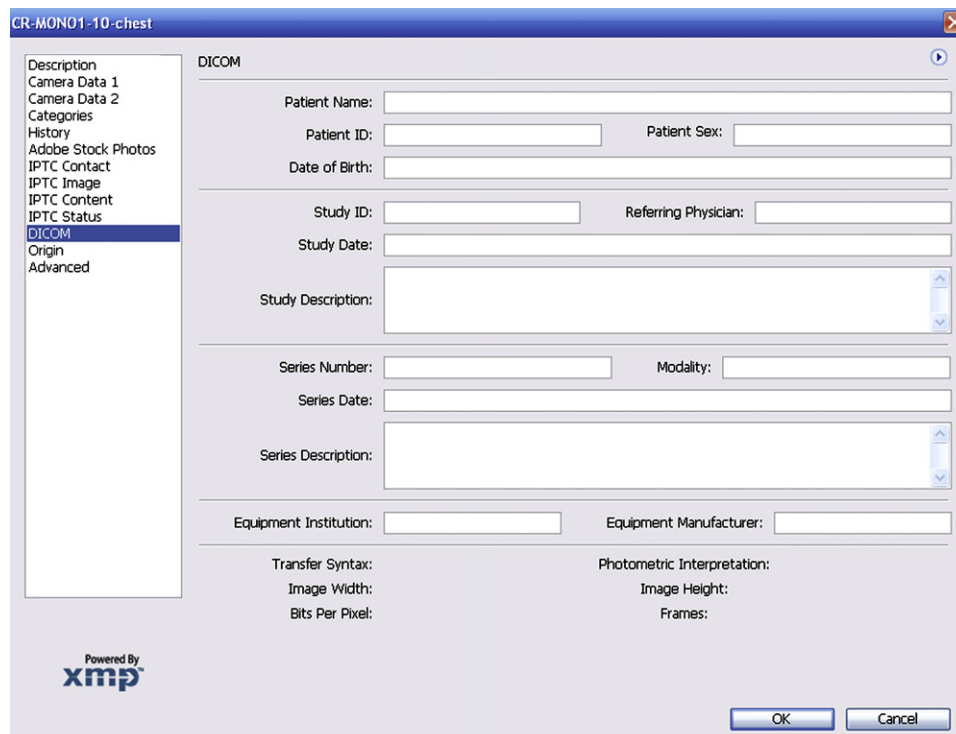
Figure 19. **Geometric Processing Effect**. Effect of geometric processing operation on an input image. The goal of the processing is to change the orientation of the input image.

contain data from multiple image files. These logs can be customized, have their data sorted into columns, and can then be exported to a text file. There is even a Scale Marker tool that can automatically add a graphic to indicate the scale of the image. Also included in the new Analysis Tools is a Count tool that can be used to number off features in an image simply by clicking on them. These data can then be sent to the measurements log for further analysis and reference.

Another interesting and useful set of tools are the Auto-Align Layers tool and HDR (High Dynamic Range) tools. These tools allow a user to import multiple images of the same subject with varying exposure values (even highly over/under exposed images). These images will be placed on separate "layers" where they will be automatically aligned and merged into a High Dynamic Range image, offering ideal exposure values throughout the entire image.

With Photoshop CS3 Extended, medical imaging personnel can now work directly in Photoshop on DICOM files with powerful editing tools at their disposal. Technologists and radiologists alike will now be able to manipulate and optimize images for output image display, resulting in better communication not only with other healthcare personnel, but with patients as well.
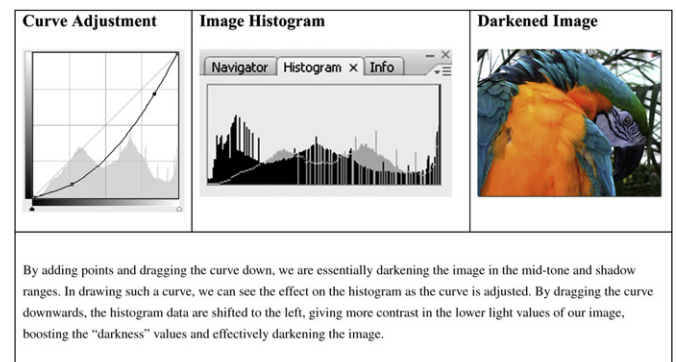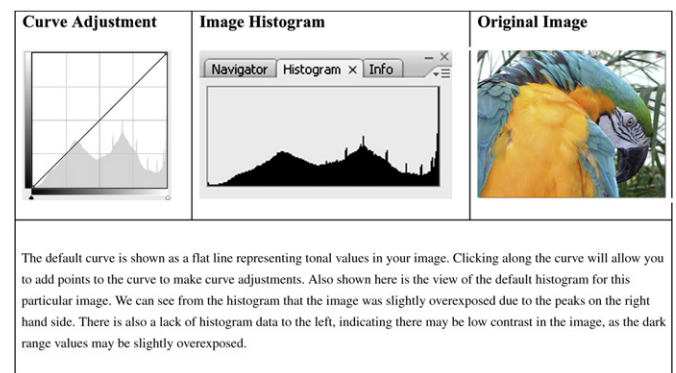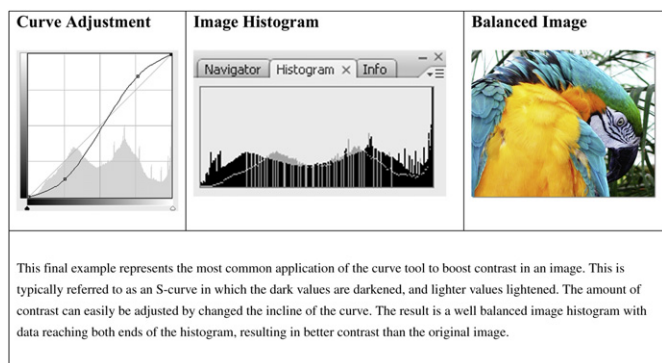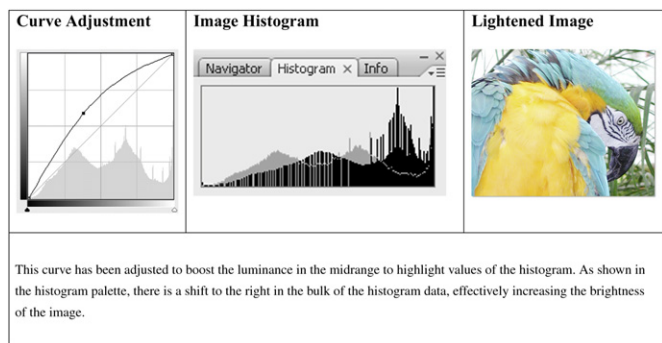
Examples of Processing Operations

One of the most powerful functions in Photoshop is the ability to manipulate the image histogram. Photoshop CS3 Extended now has a histogram palette that allows you to make changes to the histogram of your image "on the fly" while viewing the underlying original image histogram (shown as a lighter shade of gray). There are several reasons to alter an image, affecting the original histogram, as the histogram data can often reveal at a glance whether your image is over- or underexposed, flat (that is, characterized by little contrast), and in what tonal range your image needs adjusting. For digital photographers, the histograms of the red, green, and blue (RGB) light channels can be viewed and altered independently. This allows for exposure and contrast compensation, and even for colour correction to an image with a colourcast. In relationship to altering the histogram, Photoshop allows the user to change the colour space of an image from RGB, to Lab colour, to CMYK (predominantly used in the print industry), and gray scale colour spaces. Technologists and radiologists would benefit from working on images in the Lab mode colour space, as colour data could be either hidden or discarded, whereas values of lightness (otherwise known as *luminance*) could be worked on to adjust the histogram data for the image.

One of the most powerful tools in the Photoshop arsenal is the Curves tool. The Curves tool allows the user to adjust the tonal ranges of an image by clicking on the image Levels curve, and dragging on it to adjust. As changes are made to the curve, they are reflected in the histogram values shown in the histogram palette. By using the Curves tool, one can increase/decrease the contrast, brightness, and tonal range of an image. A few examples of this tool in action are illustrated below:

Although this example was done on a regular photograph, the principles and applications on medical images are the same.

Curve Adjustment	Image Histogram	Original Image

The default curve is shown as a flat line representing tonal values in your image. Clicking along the curve will allow you to add points to the curve to make curve adjustments. Also shown here is the view of the default histogram for this particular image. We can see from the histogram that the image was slightly overexposed due to the peaks on the right hand side. There is also a lack of histogram data to the left, indicating there may be low contrast in the image, as the dark range values may be slightly overexposed.

Curve Adjustment	Image Histogram	Darkened Image

By adding points and dragging the curve down, we are essentially darkening the image in the mid-tone and shadow ranges. In drawing such a curve, we can see the effect on the histogram as the curve is adjusted. By dragging the curve downwards, the histogram data are shifted to the left, giving more contrast in the lower light values of our image, boosting the "darkness" values and effectively darkening the image.

Curve Adjustment	Image Histogram	Lightened Image
	Navigator | Histogram × | Info	

This curve has been adjusted to boost the luminance in the midrange to highlight values of the histogram. As shown in the histogram palette, there is a shift to the right in the bulk of the histogram data, effectively increasing the brightness of the image.

Curve Adjustment	Image Histogram	Balanced Image
	Navigator | Histogram × | Info	

This final example represents the most common application of the curve tool to boost contrast in an image. This is typically referred to as an S-curve in which the dark values are darkened, and lighter values lightened. The amount of contrast can easily be adjusted by changed the incline of the curve. The result is a well balanced image histogram with data reaching both ends of the histogram, resulting in better contrast than the original image.

These tools allow for enhancement of particular areas of interest in an image, leading to a more clear representation in highlighting these areas. Photoshop gives technologists a high level of control over adjusting contrast and tonality in medical images, which could ultimately lead to a more accurate diagnosis.

For examples of some other useful tools applicable to the field of medical imaging, see images of the Eiffel Tower using a high-pass filter and blurring tools.

These are just a handful of the tools available in Photoshop, but they should give an idea of the potential for using Photoshop in processing and viewing medical images. Adobe may still have a long way to go before Photoshop becomes a standard in the medical imaging arena; but with Photoshop CS3 Extended, the potential exists, and the possibilities are turning into reality.

Photoshop in the Classroom

While Photoshop's main applications are in photographic image processing, it can also be used in the optimization of images for instruction, presentations, and printed learning materials. Applications for teachers, technologists, and even students are presented next.

As we know, DICOM files may contain several images representing slices of an imaging examination. An instructor could use the Animate tool in the creation of an animation of these slices, for a truly interactive and enjoyable presentation of a "scan in action". The use of image slices that are placed on "layers" in Photoshop could be used to tell a story, as different layers of a scan could be revealed or presented separately.

In some cases, the goal would be to provide a clearer picture of what is being shown in a medical image (either for instruction or diagnosis). An author, for example, could easily create a side-by-side composite image of an original image versus the enhanced (processed) one for comparison.

There is also the ability to crop, resize, and zoom in on areas of an image, which is especially helpful in publications, and
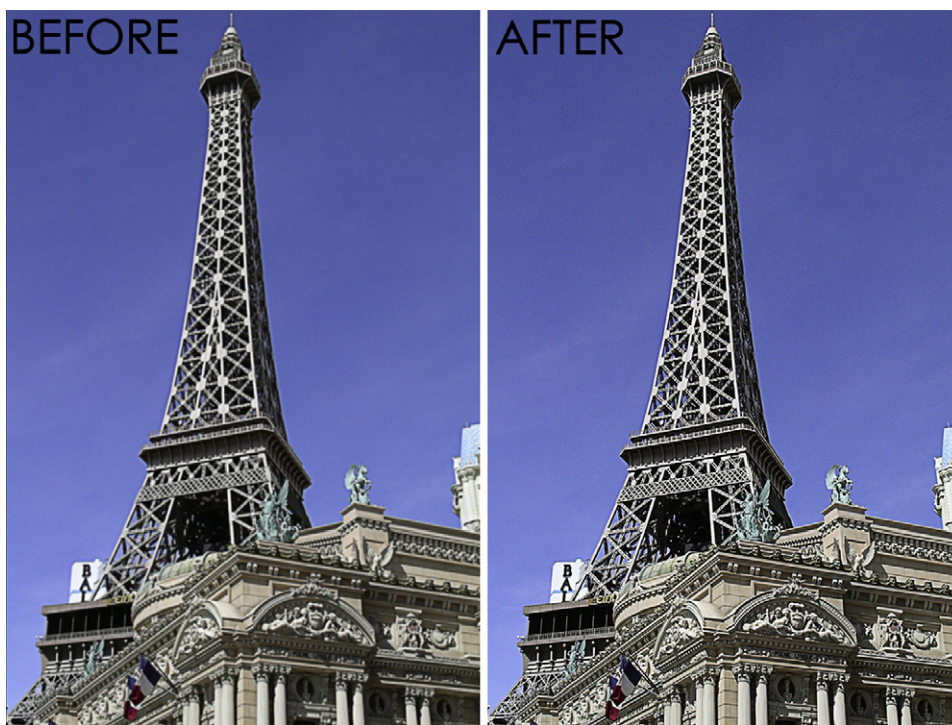
High-pass filter, used for sharpening images, and described previously in this article.
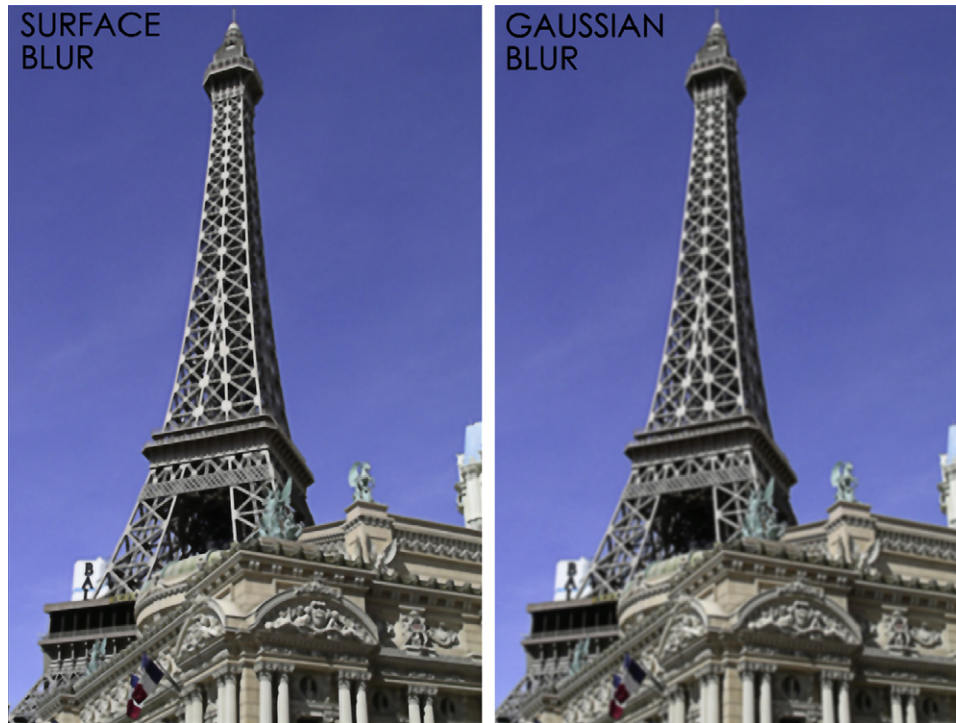
Blurring tools, such as those for surface blur, Gaussian blur, radial blur, and lens blur.

even presentations. Images can be re-sampled and optimized for web viewing (typically smaller files), or enhanced to higher resolutions to meet the requirements of printed materials and textbooks. The output of these images can be saved in several file formats; for instance, a DICOM file could be opened in Photoshop, resized or zoomed, then saved as a JPEG file for emailing to a colleague. The file could even be saved as a high-resolution TIFF file to be used in a publication.

With the processing power and tools that Adobe offers in Photoshop, it's easy to see why they have become the standard in the graphics industry. The new toolsets offered in Photoshop CS3 Extended have positioned Adobe for basic image analysis in medical imaging, with room for growth and considerable potential to become a major tool for technologists of the future.

Digital Image Compression: An Overview

Earlier in this paper, five fundamental classes of digital image processing algorithms were identified (Figure 5). In review, these include: image enhancement, image restoration, image analysis, image compression, and image synthesis. This section will highlight elements of image compression that should be in the knowledge skill-set of all digital imaging personnel.

Digital acquisition modalities, including multislice CT (MSCT) and digital mammography, can produce large volumes of digital images that are subsequently sent to a picture archiving and communication systems (PACS). PACS and Teleradiology systems have created challenges with respect to storing and transmitting large volumes of digital images. These technologies have resulted in an exponential increase in digital image files

[8,11]. For example, the number of images generated in a multislice CT examination can range from 40 to 3000. If the image size is 512 × 512 × 12, then one examination can generate 20 MB or more of data. A CR examination consisting of two images per examination with an image size of 2048 × 2048 × 12 will result in 16 MB of data. A digital mammography examination can now generate 160 MB of data [11]. In addition, Huang points out that "the number of digital medical images captured per year in the United States (US) alone is over pentabytes that is, 10^{15}, and is increasing rapidly every year [11]." In this regard, one can safely assume that similar trends apply to Canada.

One of the major ways of dealing with this challenge is the use of image compression. The goal of image compression is to solve the above problems by reducing image data storage space and increasing the speed of image transmission for large amounts of digital data, thus decreasing transmission time [9,11,13–16].

Compression Ratio: A Definition

The impact of image compression on the visual appearance of images depends on the compression ratio used in the process. The literature offers several definitions of image compression ratios [9,11,14–16]; however, one that stands out in terms of clarity is offered by Huang, who states that "the compression ratio between the original image and the compressed image file is the ratio between computer storage required to save the original image and that of the compressed data. Thus a 4:1 compression on a 512 × 512 × 8 = 2,097,152-bit image, requires only 524,288-bit storage, 25% of the original image storage required… [11]" This is clearly illustrated in Figure 20.
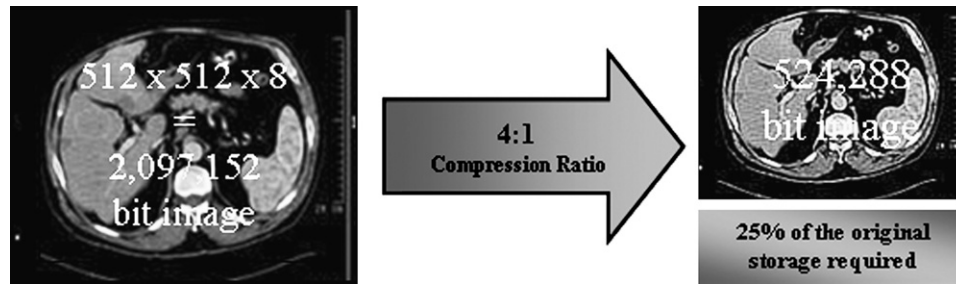
Figure 20. **The Compression Ratio**. Graphic illustration of compression ratio. If the original image size is $512 \times 512 \times 8$ (2,097,152-bit image), a 4:1 compression ratio will reduce the size to 524,288-bit image, which requires less storage space.

The above definition will serve as the basis for understanding what is meant by the term *image compression* as used in the remainder of this paper.

Image Compression Basics: A Technical Overview

It is not within the scope of this directed reading to describe image compression in any great detail; however, the more fundamental concepts (excluding all mathematics) will be outlined to provide a reasonable understanding of the technical elements involved.

Types of Image Compression

In general, there are two forms of image compression: *lossy* (irreversible) and *lossless* (reversible) compression. In lossless compression, there is no loss of any information in the image (ie, detail is not compromised) when the image is decompressed (Figure 21). By contrast, in lossy compression, there is some loss of image details when the image is decompressed (Figure 22). The latter has specific uses, especially in situations when it is not necessary to have exact details of the original image. The effect of both compression methods will be illustrated subsequently.

Lossless (reversible) compression is intended to reduce the size of the original image to speed up image transmission and reduce data storage space, the framework of which is based on two fundamental steps as described in Figure 23. One shortcoming of lossless compression is its limited compression ratio to a maximum of approximately 5:1 [5]. This means that if the original size of a digital image is 5 MB, the compressed image will be 1 MB. As noted by Brennan et al, "this may seem like a substantial reduction until one considers that irreversible compression techniques can produce compression ratios of up

to 100:1, thus reducing the size of that 5MB image to a mere 50kB [5]."

Lossless compression techniques generally examine patterns that exist in a string of bits and subsequently present the pattern in a more shortened form, thus coding the pixel changes rather than the pixel values that make up the image. One such coding technique is *run length encoding* (RLE). In RLE, any item that is repeated in the image is replaced by one value, in conjunction with the number of times that the item is repeated.

A second method of lossless compression, known as *Huffman encoding* (HE), can operate on text data as well as on images. This method uses the data to be compressed by first constructing a table of the relative frequency of the elements of the data. The table is then used to compress the data, with shorter codes assigned to those elements that occur more frequently.

A third lossless compression method for medical images is called *redundancy removal* (or *background removal*), which removes nonuseful data such as the background pixels in the digital image. thereby decreasing the size of the image file. (For further description of lossless compression techniques, readers may refer to a paper by Seeram [17].)

Irreversible Compression

Lossy, or irreversible, compression methods can compress images at much higher compression ratios, resulting in faster image transmission speeds and less image storage space requirements compared with lossless compression schemes.

Irreversible compression techniques involve three fundamental steps, as illustrated in Figure 24. These include "transformation, where the image is transformed from gray scale values to
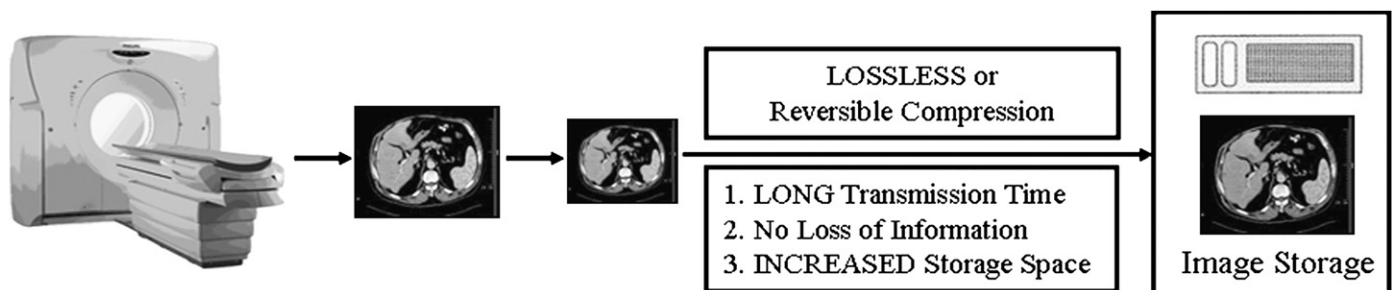

Figure 21. **Lossless (Reversible) Image Compression**. Lossless, or reversible, image compression reduces the size of the original image. The most conspicuous difference compared with irreversible compression is that there is no loss of image information content. See text for further explanation.
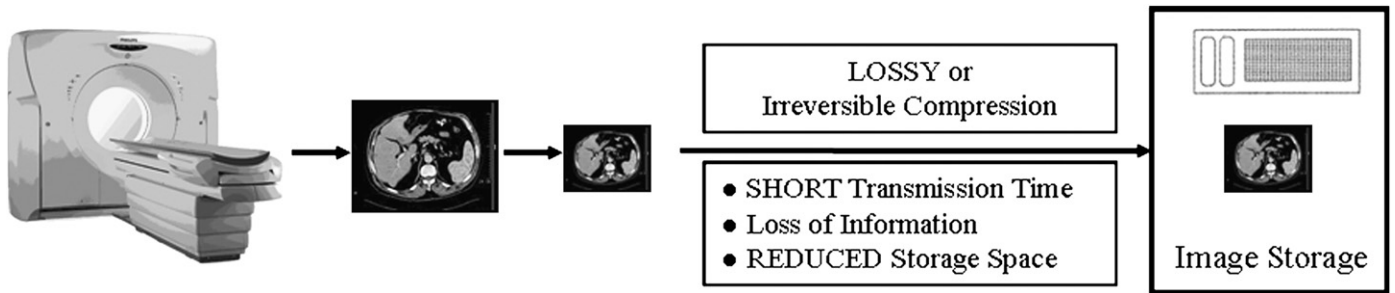
Figure 22. **Lossy (Irreversible) Image Compression**. Lossy, or irreversible, image compression reduces the size of the original image. The most conspicuous difference when compared with reversible compression is that there is loss of image information content. This type of compression reduces transmission time and occupies less storage space. See text for further explanation.

coefficients; quantization, where there is a loss of data integrity; and encoding, where reduced coefficients are presented in a compact format [14]." It is not within the scope of this paper to describe these in any detail; however, interested readers may refer to papers by Seeram [17] and Koff and Shulman [14] for further descriptions.

Techniques for Irreversible Image Compression

There are two types of techniques used for irreversible compression: *block compression* and *full-frame compression.* Block compression uses a process to compress the image in blocks, whereas full-frame compression operates on the entire image rather than blocks of the image. For a further description of these methods, readers may refer to the textbook by Huang [11].

There are two popular block compression techniques. The first is the *JPEG* (an acronym denoting the Joint Photographic Experts Group) standard and wavelet compression. The JPEG compression algorithm can be either lossless or lossy, and it was developed for both gray scale and colour images. When used on diagnostic images, lossy JPEG compression produces prominent artifacts at high compression ratios and particularly at block boundaries [14,17], and also leads to "objectionable 'ringing' around sharp edges, especially text [14]."

These problems can be overcome by the *wavelet compression technique*, also known as the *discrete wavelet transform*, whereby the image is compressed as waves. As noted by Koff and Shulman, "it involves the same steps as does JPEG: transformation, quantization, and encoding … the transform organizes the image information into a continuous wave, typically with many peaks and dips, and centers it on zero … and may break up

big images into large tiles for ease of processing. As the wavelet transform takes place, it generates progressively lower resolution versions of the wave … in addition to compressing the image, it has all the information necessary to reconstruct the image in finer detail. The result is a much better image quality than that achieved with a JPEG file [14]."

JPEG 2000 is the new wavelet compression standard, and it is now used in digital medical imaging. JPEG 2000 uses the best wavelet methods to provide improved quality, especially at high compression ratios, among other advantages. The image quality advantage is clearly illustrated in Figure 25. Ringl et al [15] have reported a comparison of the compression ratios for lossy JPEG and JPEG 2000. For example, they report that for CR/DR chest, CT, MRI, and mammography, the JPEG compression ratios for acceptable compression are 20:1, 10:1, 10:1, and 20:1 respectively. On the other hand, for the same image types listed above, the JPEG 2000 acceptable compression ratios are 50:1, 10:1, 10:1, and 20-25:1 respectively.

For a more complete and thorough description of these irreversible compression methods, interested readers may refer to the works of ratios [2,3,11,14–17]. In addition, readers will also find updates on JPEG 2000 by visiting the website http://www.jpeg.org/JPEG2000.htm.

Effect of Irreversible Compression on Visual Image Quality

At low compression ratios (8:1 or less), the loss of image quality is such that the image is still "visually acceptable [11]." The obvious concern that now comes to mind is related to what Erickson refers to as "compression tolerance," a term that he defines as "the maximum compression in which the decompressed image is acceptable for interpretation and aesthetics [18]."
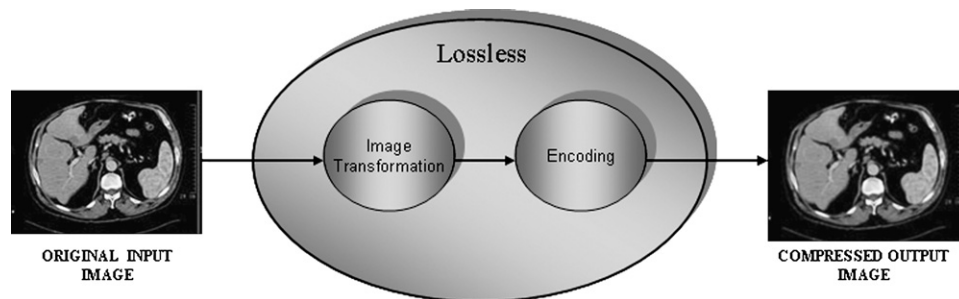

Figure 23. **Steps in Lossless Image Compression**. The lossless compression framework consists of 2 steps: image transformation and encoding.
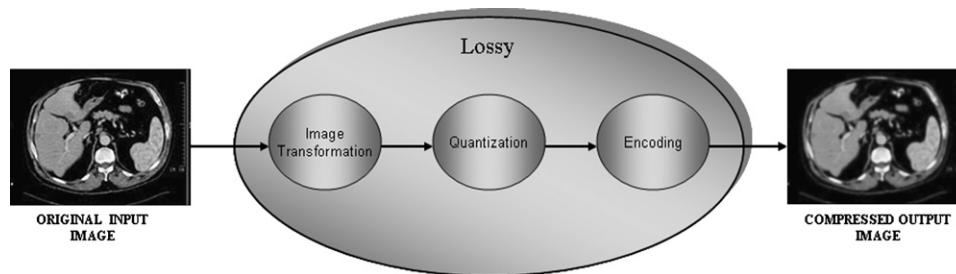
Figure 24. **Steps in Lossy Image Compression**. The lossy compression framework consists of three steps: namely, image transformation, quantization, and encoding. See text for further explanation.

Given that lossy compression methods provide high to very high compression ratios compared with lossless methods, and keeping the term "compression tolerance" in mind, Huang points out that "currently lossy algorithms are not used by radiologists in primary diagnosis, because physicians and radiologists are concerned with the legal consequences of an incorrect diagnosis based on a lossy compressed image [11]."

A recent survey by Seeram of the opinions of expert radiologists in the US and Canada on the use of irreversible compression in clinical practice showed that the opinions are wide and varied. This indicates that there is no consensus of opinion on the use of irreversible compression in primary diagnosis. Opinions are generally positive on the notion of image storage and image transmission advantages of image compression. Finally, almost all radiologists are concerned with the litigation potential of an incorrect diagnosis based on irreversible compressed images. For a comprehensive review of the literature on irreversible image compression, interested readers may refer to a paper by Seeram [16].

CAR and the Use of Irreversible Compression

The use of high compression ratios while maintaining image quality in clinical imaging is possible. However, it appears that because lossy (irreversible) compression does not preserve all the information contained in the original image, there may be legal consequences facing radiologists. Therefore, CAR "has accepted the principle of irreversible (lossy) compression for use in primary diagnosis and clinical review, using DICOM JPEG or JPEG 2000 compression algorithms, at specific compression ratios set by image type [14]." At present, CAR does not support the use of irreversible compression for digital mammography.

Image Postprocessing: An Essential Tool for Digital Imaging

Digital image postprocessing is now a routine activity in digital medical imaging and it is also an essential tool in the PACS environment [19]. Technologists and radiologists are already actively involved in using the tools of image processing, such as the digital image processing operations and techniques outlined in this article. Training programs for both technologists and radiologists are also beginning to incorporate digital image processing as part of their curriculum. Such activities will only serve to improve communications with radiologists, medical imaging physicists, and biomedical engineers, and with equipment vendors as well.

A course on image postprocessing for medical imaging technology programs may include topics such as the nature of digital images, image processing operations and their applications in
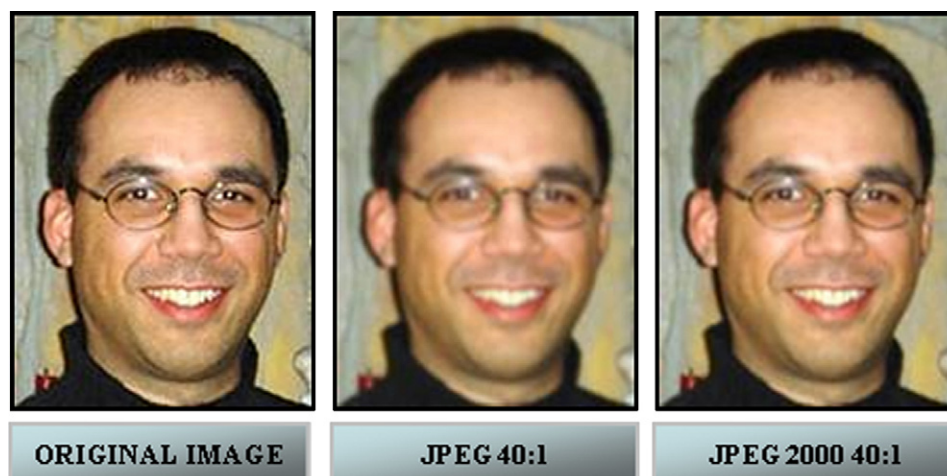

Figure 25. **Compression Algorithms and Visual Clarity**. The effect of JPEG and JPEG 2000 compression algorithms on picture clarity. JPEG 2000 is now used routinely in digital radiology. (Images courtesy of David Seeram.)

digital radiology, including specific postprocessing operations in CR, DR, CT, MRI, digital subtraction angiography, digital fluoroscopy, 3D imaging, and image compression fundamentals [20]. Finally, programs may use Photoshop for laboratory exercises that students can engage in to strengthen and enhance their understanding of image postprocessing.

About the Authors

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