

DIGITAL IMAGE PROCESSING

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Image processing or digital image manipulation is one of the greatest advantages of digital radiography (DR). Preprocessing depends on the modality and corrects for system irregularities such as differential light detection efficiency, dead pixels, or dark noise. Processing is manipulation of the raw data just after acquisition. It is generally proprietary and specific to the DR vendor but encompasses manipulations such as unsharp mask filtering within two or more spatial frequency bands, histogram sliding and stretching, and gray scale rendition or lookup table application. These processing steps have a profound effect on the final appearance of the radiograph, but they can also lead to artifacts unique to digital systems. Postprocessing refers to manipulation of the final appearance of the radiograph by the end-user and does not involve alteration of the raw data. *Veterinary Radiology & Ultrasound, Vol. 49, No. 1, Supp. 1, 2008, pp S42-S47.*

Key words: computed radiography, digital radiography, radiographic image processing, unsharp mask filter.

Introduction

IN CONVENTIONAL SCREENFILM radiography, the film emulsion must be processed to convert the captured latent image into a viewable radiograph. The processing of conventional film screen exposures (development and fixing) is standardized and cannot be easily altered. One of the best advantages of digital radiography (DR) is the ability to use image processing. Image processing is a broad term that generally encompasses all of the processes applied to the detector and the data set of a radiographic exposure before the study is closed on the acquisition device. This term can cause some confusion but in general, must be applied to the raw data gathered by the digital imaging system in order to render an image that is reminiscent (in appearance) of a screen-film radiograph. Whereas the appearance of a conventional screen-film radiograph is largely dependent on the characteristics of the screen-film system and cannot be manipulated, digitally captured radiographs can be modified so that actual pixel values are altered and manipulated by varying the gray scale or lookup table (LUT) application. Physicists generally divide image processing into three main categories: (1) preprocessing, (2) processing, and (3) postprocessing.¹⁻³

Preprocessing

Image preprocessing refers to the initial steps that are applied to the raw imaging data and is generally out of the

hands of the imaging device operator or the end-user, the radiologist. These methods account for defects, imperfections, and non-uniformity in the detection system and are usually built into each manufacturer's system. The way in which preprocessing is performed will depend on the readout character of the detector system. Point scan systems (laser-based computed radiography [CR]), linear scan systems (newer CR and some charged-couple devices [CCD]), and two-dimensional fixed array systems (CCD, direct and indirect DR) will require different forms of preprocessing to correct for system imperfections.

In one-dimensional readout systems (point scan or linear scan), the center of a CR imaging plate is more efficient than the periphery resulting in differential light collection efficiency. To correct this inhomogeneity, a uniform X-ray exposure is used to identify the variability, the data are inverted, and then applied to the readout to give a more uniform output.² Lens-coupled CCD systems have a unique preprocessing step that corrects for geometric distortion caused by lens divergence at the periphery of the image.

In two-dimensional detector arrays and CCD linear arrays, it is expected that some pixels will be nonfunctional or "dead." After manufacture or after calibration, a dead pixel map is generated for each detector. This map identifies the dead pixels, and a value for the dead pixel is interpolated by averaging the surrounding pixel values. More than one adjacent dead pixel will result in inadequate dead pixel correction. If dead pixels become visible on the processed digital images, this may indicate that pixels have lost function over time and that the detector needs reanalysis.²

Manufacturers will correct for the systemic imperfections differently, and this discussion refers to theoretical

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doi: 10.1111/j.1740-8261.2007.00333.x

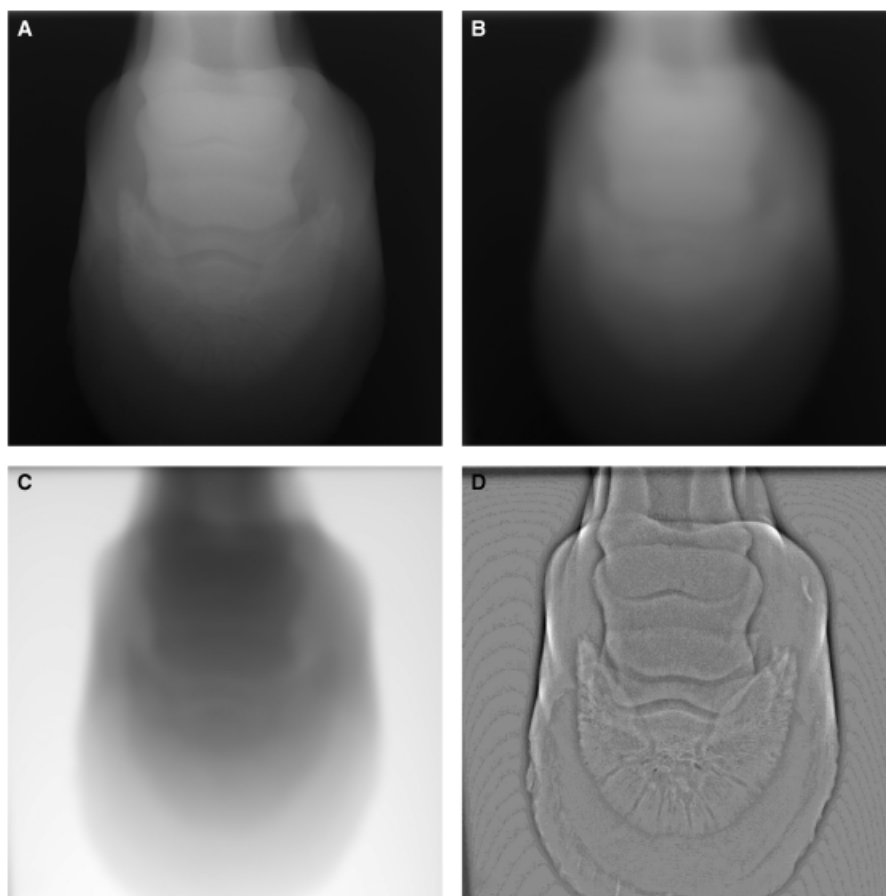


FIG. 1. (A) This image represents unprocessed data from a dorsopalmar radiograph of an equine foot. (B) An unsharp mask with a large kernel resulting in a blurred image. (C) The blurry image is inverted and then added (effectively subtracting B from A) to the original image shown in (A). (D) A radiograph processed to emphasize high spatial frequency structures. The overlying pattern of the wooden block on which the foot was placed is now evident while it was not on the original study.

examples of correction strategies. Two-dimensional detector arrays are affected by dark noise, which refers to the electronic noise associated with each detector element in the absence of radiation. Multiple dark images or images made in absence of radiation are acquired, averaged, and subtracted from an actual image in order to minimize the effect of dark noise. Furthermore, inherent variability is present between individual detector elements within an array and large array detectors amplify the signal arising from each detector element. This combination can result in the amplification of the subtle variability of the detector elements producing an obvious banding pattern in different regions of the detector. Averaging multiple images made with a uniform X-ray beam produces a gain image. This is then used in concert with the dark image to correct for the system imperfections and produce a more uniform data set.^{1,2}

All of these corrections are applied at the level of the detector system with the goal of eliminating artifacts introduced by the hardware. These corrections precede the actual acquisition of a diagnostic radiograph. When a di-

agnostic radiograph is acquired, that data set is processed to produce an image that will be used to make a diagnosis.

Processing

When a DR is made, a rectangular pixel matrix with discrete pixel values representing the measured exposure (usually through quantization of light conversion) is generated. Digital detectors are characterized by a very wide dynamic range, defined as the range of exposure values over which a diagnostic image is produced, and linear response to X-ray photons. This is touted as another advantage of DR. Because most detectors systems use either 10 or 12-bit depth, the number of gray shades represented (2048–4096) will greatly exceed the number of gray shades detectable by the human visual system. Furthermore, the large range of gray scale values will result in very low contrast resolution that, in certain anatomic regions, will make it difficult or impossible to identify lesions.⁴ Image processing is designed to convert the raw digital image to an optimal or usable radiographic image. The goals of image

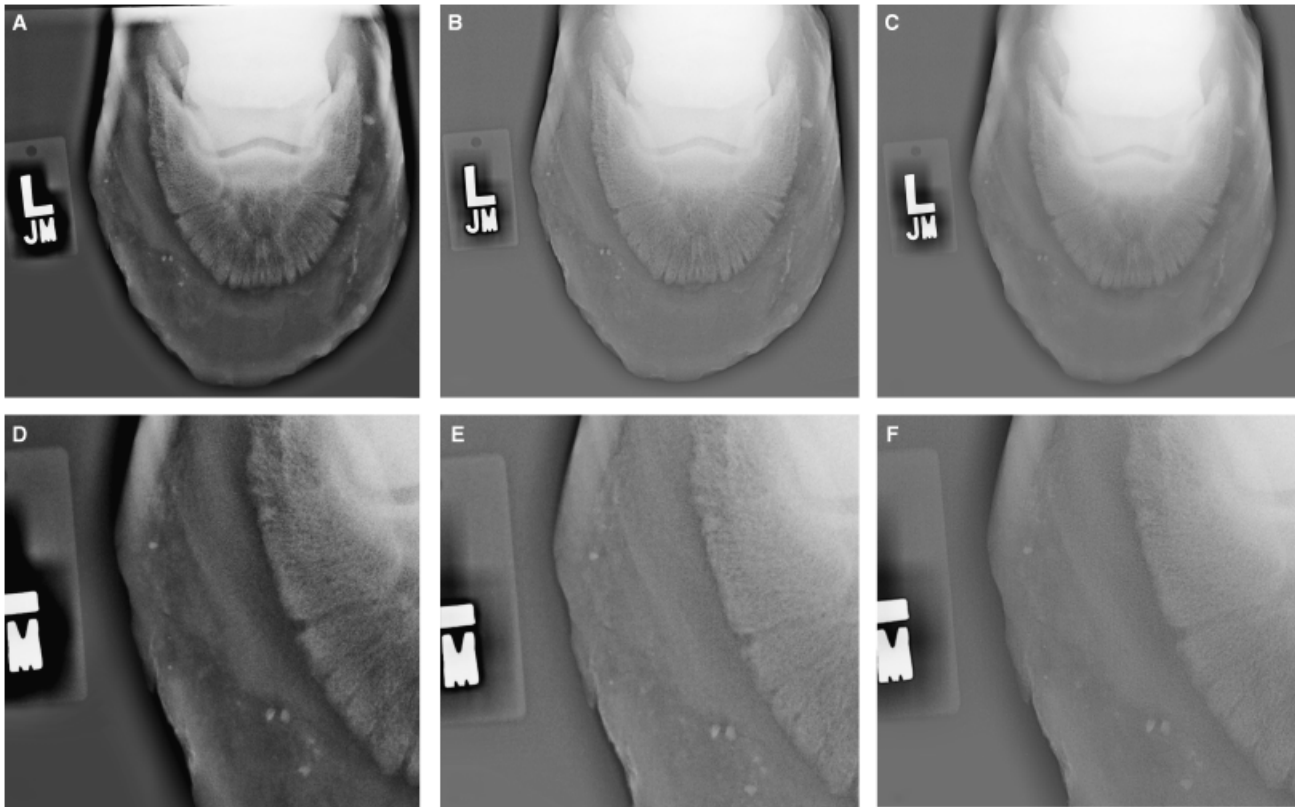


FIG. 2. All of these images were processed using unsharp mask filtering provided by Fuji CR. Images were processed using a large kernel (A), a medium kernel size so that the predominant effect is one of edge enhancement (B), and a small kernel size where increased detail of small structures is expected (C). The images D–F are magnified. For all images, the filters were applied with the same strength. Notice the large halo of lucency surrounding the metallic letters. This artifact can cause clinically significant confusion if it surrounds metallic implants within bone.

processing are to display the full object range, to improve local contrast, to optimize spatial resolution of the digital system, and to suppress image noise.^{3–5} Improving contrast, spatial resolution, and decreasing noise are achieved by actual manipulation of the raw data set. Displaying the full object contrast using gray scale values similar to those that would be displayed on screen–film is a product of gray scale rendition or LUT application whereby the actual data is unaffected.

A DR hosts information in a pixel matrix. Information can be derived from this pixel matrix regarding spatial (X , Y location), spatial frequency defined as the number of times the object can be repeated per unit of distance often discussed in line pairs per millimeter (size, sharpness), and amplitude (exposure value). A digital image can be decomposed and manipulated using any of these features. High spatial frequency information describes small things such as pulmonary nodules, bone trabecular patterns, and interstitial pulmonary markings. Unfortunately, high-frequency information usually also describes the major component of image noise. Low spatial frequency information includes larger objects and contributes to overall changes in image darkness.^{3,4} An image can be manipulated by the

application of a spatial filter, which in effect, results in the emphasis or de-emphasis of specific ranges of spatial frequency.

One of the basic methods of image processing is termed unsharp mask filtering and is discussed to illustrate the concept of spatial frequency processing. A variation of this method is used by Fuji CR*. This unsharp mask filtering technique decomposes an image into high- and low-frequency components, subtracts or adds one of the two, producing an image that either enhances higher spatial frequency details (edges) or suppresses lower spatial frequency details.⁴

In order to produce a high frequency enhanced image, A^* , using unsharp mask filtering a series of steps must occur. First, a low-pass filtered image (blurred image), B , is subtracted from the original, A . This resultant image is then added to the original with a weighting or enhancement factor (f). Mathematically, the overall enhanced im-

*Fuji FCR 5000 Plus, Fujifilm Medical Systems, 419 West Avenue, Stamford, CT 06902.

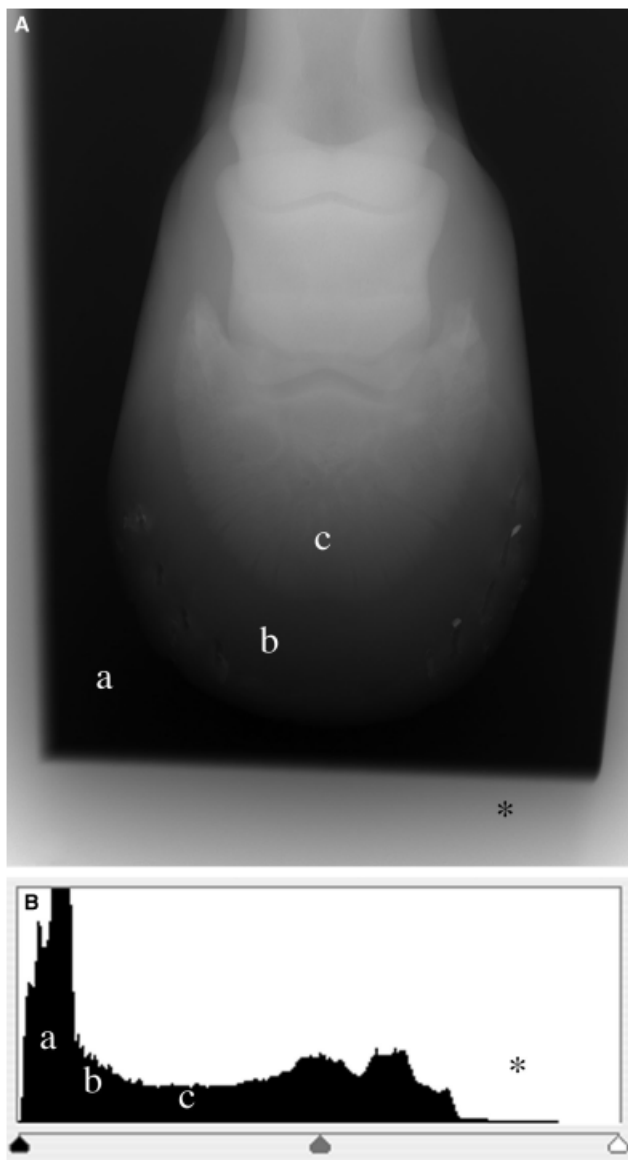


FIG. 3. (A) Unprocessed radiograph. There are regions that are outside of the collimator, outside of the anatomy, and then variable radiographic opacities within the anatomy. (B) Histogram representation of the radiograph in (A) representing the frequency of occurrence on the y-axis and the optical density on the x-axis. Regions from the radiographs denoted by a, b, c, and * are represented in the histogram.

age (Fig. 1) is represented by the equation:

$$A^* = A + f(A - B)^4$$

There are two ways in which the effects of unsharp mask filtering can be altered. The first is by the f , which will determine the strength of the applied filter, and the second is by altering the kernel size used in the filter (or the cut off frequency for low-pass filtering). When a filtered image is produced, it is blurry because the pixels within the filter kernel are averaged to give one number representing that

region. The size of the filter kernel will determine the overall effect on the processed image. The kernel size determines the cutoff between structures that are enhanced and suppressed. A small kernel will result in enhancement of very small structures and actually improve modulation transfer function, whereas a medium kernel will result in edge enhancement. A very large kernel size will result in dynamic range compression and an overall impression of increased detail (Fig. 2).⁴⁻⁶ Large enhancement factors can lead to edge artifacts (potentially mimicking clinically significant lesions such as bone resorption around metallic implants) and increased image noise.

Multiscale processing is a more advanced form of spatial filtering whereby the image is decomposed into multiple spatial frequency bands. Unlike unsharp mask filtering in which two sub-images (high and low frequency) are produced, multiscale processing subdivides the image into multiple sub-images based on structural size. Filters are then applied to each sub-image. This allows for manipulation of specific frequency bands and enhancement of local contrast.⁶ Those objects that are relatively low contrast can be enhanced while those that are of high contrast can be suppressed. This effectively compresses the dynamic range of the image without creating edge artifacts.

The processes discussed above, unsharp mask filtering and multiscale processing, have a profound effect on the final appearance of a radiograph. Both of these processes involve manipulation of the raw data. The following discussion refers to alteration of the display characteristics of the image without manipulation of raw data.

When a DR is produced, a wide range of exposure values are recorded. These values will include areas outside of the collimator that have very little exposure adjacent to the areas outside of the anatomy but within the collimator where direct exposure to the X-ray beam is recorded. This can be represented in histogram format (Fig. 3). In most systems, exposure recognition is automatic and the lowest and highest pixel values are accordingly assigned. In some systems, areas outside of the collimator and areas outside of the anatomic region of interest are detected and excluded from the automatic assignment of output pixel values. This feature will result in histogram sliding and stretching. If the detector records very high or very low exposures, the entire histogram can be shifted to compensate for these regions. Similarly, if segmentation of the lowest pixel values and the highest pixel values occurs, it is appropriate to stretch or widen the histogram so that the pixel values are more evenly distributed over the potential range. If a problem occurs whereby an image appears either too dark or too light, the technician can redraw a region that more closely approximates the area of interest thereby recreating the histogram and exposure recording.

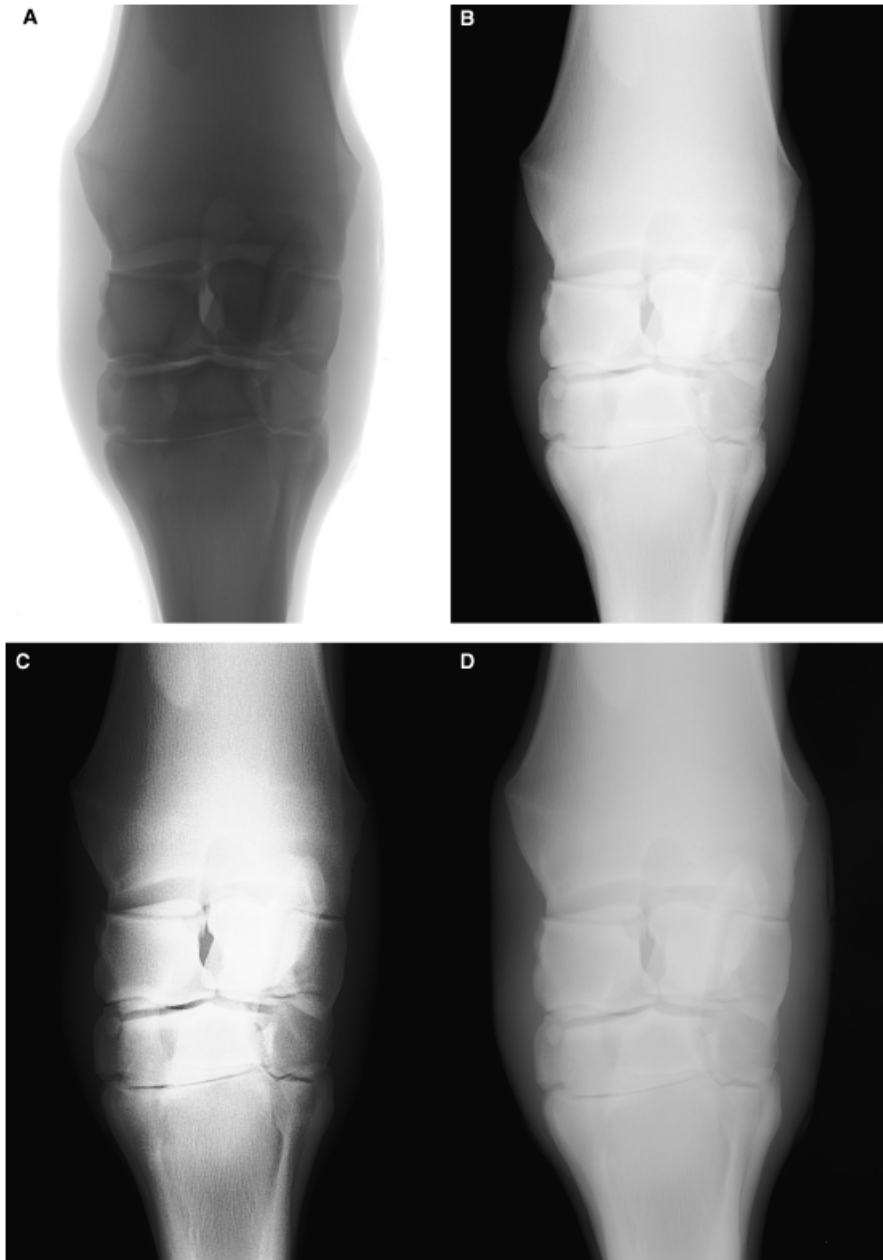


FIG. 4. These images are dorso-palmar radiographs of an equine carpus with four different lookup tables (LUTs) applied. (A) A radiograph with an inverted LUT. (B) A relatively standard LUT. (C) A LUT with a steep slope. (D) A LUT with a very low slope. Note that images C and D have a similar appearance to very high contrast (C) and very high latitude (D) screen-film combination radiographs. Inappropriate LUT application can result in loss of clinically relevant information such as the clipping of the soft tissues in (C).

Gray scale rendition or LUT application is performed at the level of the acquisition device and can be altered by the operator. This operation does not mathematically alter the raw data, it merely controls the way the data is displayed on the output device. For this reason, LUT application is different from some of the previously mentioned processing techniques. However, inappropriate selection of LUT can result in loss of information for the end-user. Each input pixel value is assigned a new output

value based on the LUT. Historically, the graphical representation of the LUT has closely resembled the shape of an H&D curve so that the output image closely resembles an analog screen-film radiograph. Very high and very low exposures will be represented as black and white and the remaining intermediate exposure values will fall in the middle of the sloping portion of the LUT curve. Most vendors have several different LUT curves that may be appropriate for certain anatomic regions that are mostly

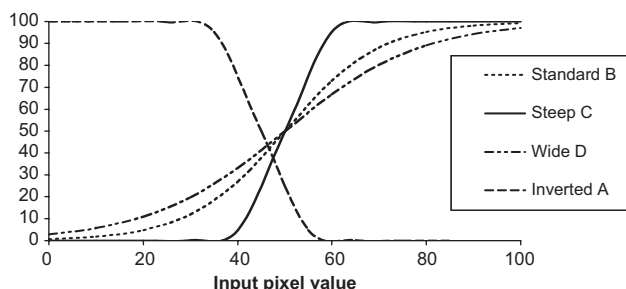


FIG. 5. Graphical representation of the lookup tables used in Figure 4.

defined by the slope of the intermediate portion of the curve (Figs 4 and 5).

Postprocessing

Once raw digital data has been processed using algorithms described above, the final image can then be sent to the viewing monitors. At the viewing station, image contrast and brightness can be further manipulated with windowing and/or leveling. Window refers to the range of pixel values that are displayed out of the available pixel values. Viewing with a wide window generally leads to lower contrast while viewing with a narrow window leads to higher contrast. Level refers to the midpoint of the pixel values that are displayed. Increasing the level generally increases the brightness of the image.

Most DICOM viewing software and some proprietary viewing programs have additional postprocessing functions that allow the end-user to manipulate the appearance of the radiograph. These manipulations are generally tran-

sient. The image will be stored in its original format but displayed with the chosen application for the viewing session for as long as the viewer requires. Some of these manipulations include image sharpening, edge enhancement, and smoothing. Further functions included in some viewing programs allow the end-user to change the LUT and therefore dramatically alter the appearance of the radiograph. As a general rule postprocessing steps can aid the diagnostician but do not alter the stored radiographic image.

Summary

Each manufacturer uses some variation of the above techniques to process the raw digital images. The specifics of the algorithms that are used in each system are often proprietary. The end-user generally has very limited control over the final appearance of the image. At the level of the acquisition device, different vendors offer access to some parameters and LUTs. Image processing is powerful and creates high-quality radiographic images. The same processing techniques can lead to artifacts that are unique to the digital modality. Having a basic understanding of the processing algorithms allows the user to optimize the resulting image and avoid the pitfalls of artifacts. For more information about DR artifacts, see another article in this Supplement.⁷

Disclosure of Conflicts of Interest: The authors have declared no conflicts of interest.

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