Chapter 4

Image Reconstruction and Review

Data acquisition with MDCT scanners is relatively straightforward. Scanners offer a fixed number of slice thickness options, and other variables are controlled in predictable ways for different examinations. When it comes to image reconstruction and review however, the opposite is true. There are almost an unlimited number of ways to reconstruct and view an MDCT data set, and no one right way to do it. Many of the choices made depend on variables that are site and radiologist dependent and have nothing to do with the scanner or the examination performed. Questions to consider when designing reconstruction protocols include the following: How will the images be viewed—on a PACS monitor, on film, or directly on a 3D–capable workstation? What is the archival method—film or electronic storage? If the storage is electronic, is it on-site or remote? What is the cost structure for the storage? Finally, many of the choices will come down to the personal preferences of individual radiologists. These preferences frequently change and evolve as radiologists gain experience with volumetric imaging.

Image Reconstruction

If you could summarize a basic principle of time-efficient volumetric imaging with MDCT in a few words, they would be scan thin, view thick. It is important to remember that the thinnest images that can be reconstructed for a data set is predetermined by the slice thickness used for the scan. Also, the thinner the sections available, the better the quality of derived multiplanar and 3D reconstruction. Once these thin sections are obtained, all scanners offer tremendous flexibility in the way images are reconstructed and reviewed. Some of the parameters to consider when reconstructing the data set include reconstruction method and algorithm, FOV, slice thickness, and automated or manual creation of MPR, volume, or maximum intensity projection (MIP) images.

Reconstruction Algorithm

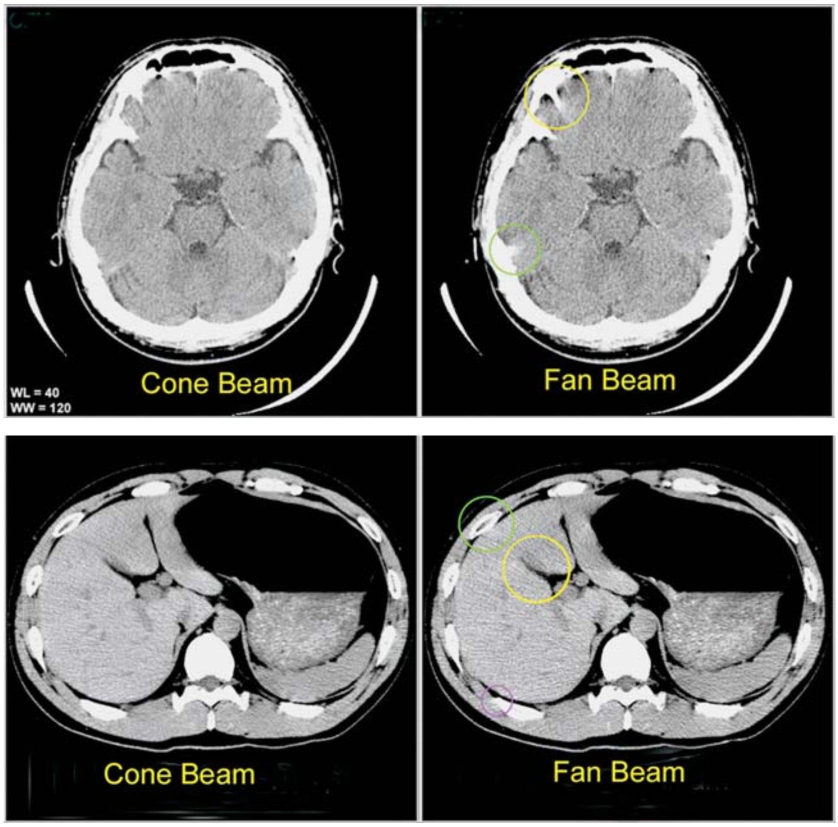
Image reconstruction with 16-slice and higher MDCT scanners is much more complicated than with single-slice or even 4-slice scanners. Axial scanning with single-slice scanners is relatively straightforward, as all of the views needed to reconstruct an image are acquired in the image plane, since the table does not move while the image is being acquired. With the introduction of helical or spiral scanning, image reconstruction had to take a considerable leap forward, because now the table was moving continuously during data collection, and the views needed to reconstruct the axial image were not all in the same plane. To overcome this problem, views in the image plane were interpolated from measurements on either side of the image plane. The most practical result of helical image reconstruction was a broadening of the slice sensitivity profile for a given image. This means that the actual reconstructed image was thicker than the slice thickness at which it was acquired, particularly with higher pitches. This effect was small with single-detector scanners. The advent of 4-slice scanners required minor modifications to the existing helical reconstruction algorithms, which were still functional.

The introduction of scanners with more than 4 simultaneous slices created further complications. Existing algorithms that assumed the x-ray source, imaging range of interest (ROI), and the detector were all in the same plane were no longer completely valid. Newer algorithms that accounted for the fact that the imaging ROI actually projected onto multiple detector rows in different planes were needed. Trying to reconstruct axial images without taking these various view angles (cone beam) into account produced significant artifacts. In order to maintain image quality, various cone beam reconstruction algorithms were developed. Because these new techniques are very computer intensive, image reconstruction times tended to be significantly longer than for single- and 4-slice scanners. Manufacturers have compensated for this by incorporating faster processing boards into the 16-, 32-, and 64-slice scanners.

It is important to appreciate that the reconstruction algorithm chosen can have a significant effect on image quality and artifacts. Artifacts become more pronounced as the cone angle increases, and at the periphery of the field of view. Edge distortions and blurring at high-contrast interfaces are common examples of reconstruction artifacts. It is not uncommon for current systems to provide both cone beam and conventional reconstruction (fan beam approximation) algorithms, giving the operator a choice between reconstruction speed and image quality (Figure 4.1). Many scan manufacturers quote very high reconstruction rates for CT images that are not based on using a full cone beam algorithm. These reconstruction speeds may be useful in some cases, but the majority of cases should be reconstructed with the best quality algorithm.

Reconstruction Filters

Once the basic reconstruction algorithm is chosen, a choice of filter kernel to be applied to the raw data must also be made. There are mul-



A

B

Figure 4.1. Reconstruction artifacts. (A and B) Brain and abdomen CT images reconstructed with two different algorithms (cone beam and fan beam approximation). Note the more pronounced artifacts with the non–cone beam reconstruction. Windmill and streak artifacts are most pronounced at the periphery, best noted involving the skull and ribs. Note also the blurring of the liver margin (yellow circle). (Courtesy of Ilmar A. Hein, PhD.)

tiple filter options varying between the extremes of very smoothing to very sharpening filters. These filters can have a tremendous effect on how the final images look. In general, smoother (soft tissue) filters are more often used to reconstruct the raw data, as sharper filters will often produce images that are unacceptably grainy, particularly when looking at very thin slice sections. Smoother soft tissue reconstruction kernels also generally produce better-looking 3D volume and surface reconstructions.

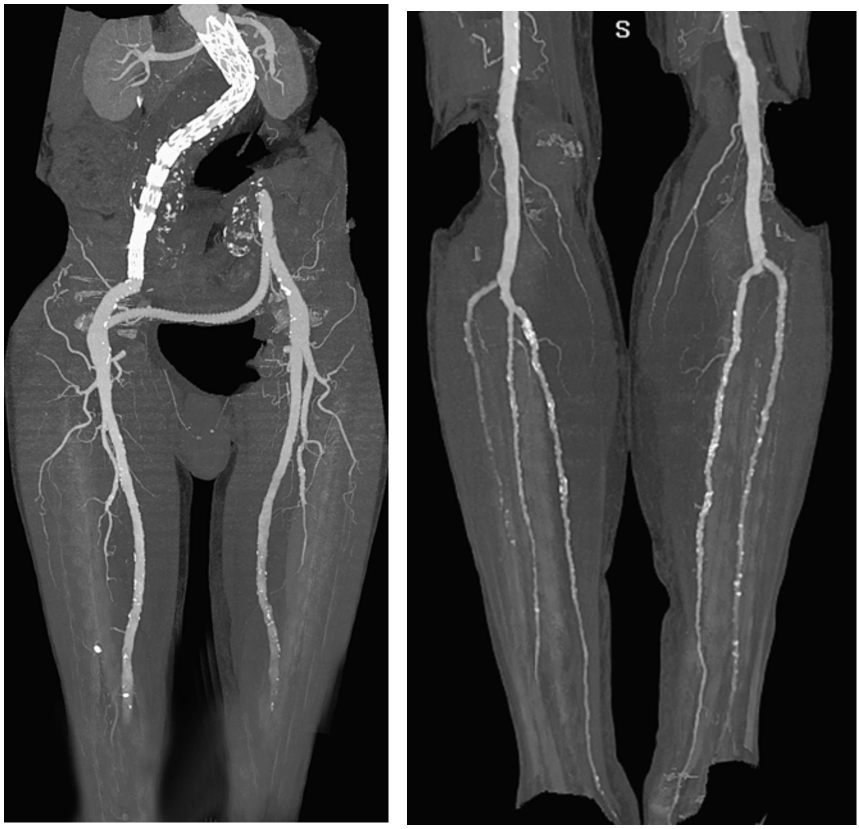
The raw data can be reconstructed with as many different filter kernels as necessary to provide the desired information. For example, chest scans can be routinely reconstructed with both a soft tissue filter as well as a sharper filter to better see lung detail. Another way to achieve a similar look and save storage space and reconstruction time is to apply an edge enhancement algorithm to the images after they are reconstructed. Most PACS systems allow for a sharpening filter to be applied to the images as a postprocessing feature. This approach is not quite as good as applying the filter directly to the CT raw data, but it can be a good compromise for sites that want to decrease the number of images reviewed and stored and speed up reconstruction times. Special filters can also be applied on the scanner for orthopedic cases to reduce artifacts from metal in patients being scanned with rods or joint prostheses in place.

Manufacturers of CT scanners can recommend certain kernels for reconstruction of images for different types of cases, but I recommend that each site work with its applications people to try out various options and choose the filters that they like best for each different examination. Applications specialists can take the same data set and reconstruct images using different filters for direct comparison by the radiologists. The decision whether to reconstruct the data in a single (soft tissue) algorithm or multiple algorithms (soft tissue, lung, bone) must be decided by each site. The benefits of multiple reconstructions are better image quality for bone studies and lung, but the disadvantages are significant and include longer reconstruction times for each case and much more data to review and archive. Also, much of the same effect can be achieved using postprocessing features on a PACS workstation.

While discussing image reconstruction, real-time, or continuous, imaging should be considered. This specialized algorithm allows CT images to be viewed as rapidly as 12 frames per second. Originally developed for CT fluoroscopy to facilitate and speed up CT-guided interventions, the technique has other valuable applications. It can show the operator the results of a helical scan in real time, providing greater control over when to terminate or extend the scan. On occasion, physicians are able to make important decisions about trauma patient care even before the final images are reconstructed. Perhaps the most valuable application, however, is the use of real-time imaging for contrast tracking. Scan timing to achieve optimum contrast enhancement has been getting more and more difficult since the introduction of helical scanning. Considering the scan speed of 16 and higher slice scanners, the situation is even more critical. Real-time reconstruction is able to monitor contrast with CT number measurements as high as 12 frames per second, thus eliminating any uncertainty in scan timing. The more sophisticated of these software packages can start the helical scan automatically or show the operator the best time for manual initiation. The software can be sufficiently robust and reliable for all contrasted CT studies, including coronary angiography. Real-time reconstructions also allow a CT technologist to instantly evaluate a contrast injection for quality of vascular enhancement. For example, when performing a CT runoff, if the scanner has "outrun" the contrast bolus to the legs, a second scan can be performed immediately to identify the vessels (Figure 4.2).

Slice Thickness

Thin (submillimeter) images are wonderful for generating volume reconstructions but are less than ideal for primary image review. These



A B

Figure 4.2. Runoff with second pass through the lower legs. (A) An 88-year-old man with severe generalized arteriomegaly and prior aorto-right femoral graft with femoral-femoral crossover graft. Segmented MIP image demonstrates no flow below the distal superficial femoral arteries. Because of the generalized arteriomegaly, flow is extremely slow and the scanner has outrun the contrast bolus. (B) Additional scan obtained through the lower legs immediately following the initial runoff. Utilizing the real-time reconstruction feature, the technologist could see the absence of contrast in the calves and performed a second pass. Segmented MIP image shows the distal runoff.

data sets are large and cumbersome to review even on the best PACS systems. The images tend to be noisier, and pathology is frequently better identified on thicker section images. Radiologists are generally more likely to identify important findings when looking at 200 images as opposed to 800 images. The goal is to maintain the advantage of high-resolution imaging but to create image files that are manageable and easily reviewed, and to prevent the eyestrain and fatigue associated with viewing huge data sets. Time-efficient review is critical to gaining acceptance of MDCT. When presented with overly large data sets, both radiologists and clinicians will eventually become frustrated, and error rates may increase because of image fatigue.

Another important characteristic of multislice image reconstruction was alluded to at the beginning of this chapter. Since the acquired data sets are highly sampled volumes, it is quite feasible to construct images that are considerably thicker than the slices used during scanning. The technique is similar to averaging or filtering the raw data over any desired image thickness. This can have considerable value when thin images are needed for MPR or 3D reconstructions, but thicker images are preferred for interpretation and archiving. It has become convenient to distinguish between slice thickness (how the data were acquired) and image thickness (how the data are reconstructed). Keep in mind that image thickness may be greater than—but can never be less than—the slice thickness at which the data were acquired. Review of thicker slice axial and multiplanar images is a fundamental component of time-efficient CT workflow.

The image thickness chosen for reconstruction is a highly individual decision and may depend on the type of examination, indication, and how the images are reviewed (soft versus hard copy). For soft copy viewing on PACS, reconstruction slice thickness between 3 mm and 5 mm will cover the vast majority of examinations. This is perfectly adequate for the majority of body, neurology, spine, and extremity studies. There are certain examinations, however, in which review of thinner reconstructions (1.5 mm to 2 mm) may be useful. Some examples include chest angiogram for pulmonary embolism, pancreas evaluation, peripheral joints, and chest for lung nodule or high-resolution evaluation.

If image review must be done on hard copy, then even thicker reconstructions are generally used to keep film number and cost more reasonable. It should be emphasized that no matter what image thickness is chosen for viewing, the thin section data remain available and can be reviewed in any case in which there is a question or problem that might be answered by very high resolution images.

Overlapping Reconstructions

Conventional CT wisdom dictates that to achieve high-quality multiplanar and 3D reformations the images should be reconstructed with an overlap of approximately 50%. Therefore, for cases scanned at 1.5-mm collimation, the images should be reconstructed every 0.75 mm. For the example cited, this would in fact improve quality of MPR and volume images. The down side is, of course, larger data sets that take up more memory and storage.

With current generation 16 or higher detector scanners, overlapping reconstructions are often unnecessary. When scans are generated with isotropic voxels, improvement in reconstruction quality from overlapping reconstructions is often quite minimal. In patients scanned with smaller FOV and resolution of 0.5 mm, overlapping reconstructions are generally not worth the extra difficulty generated by the larger data sets. The same is also true of larger FOV examinations with resolution up to 1 mm. Different scan manufacturers have different recommendations regarding overlapping reconstructions. With scanners having a maximal resolution of 0.75 mm, overlap is generally recommend, whereas with scanners having a resolution of 0.5 mm, this has been found to be unnecessary in most cases. I would recommend that each site experiment with several different types of CTA cases and reconstruct the same data set with and without overlap and compare the quality of the MPR and volume images for themselves to make a final determination.

Multiplanar Reconstructions

A fundamental benefit of volumetric data sets is the ability to quickly and easily review very high quality multiplanar images. With MDCT, multiplanar imaging should be part of the routine practice and incorporated into almost all CT examinations in some form. Standard thicker section (3 mm) coronal and sagittal images are simple to create and can be reviewed quickly and efficiently (Figures 4.3 and 4.4). For years radiologists relied on axial images for primary diagnosis. Although multiplanar reconstructions were available, there was substantial image quality degradation between the axial and the reconstructed images. Few radiologists in this setting felt comfortable relying primarily on the reconstructions for diagnosis. MDCT has completely changed this. Radiologists are now free to interpret images in whatever plane is most appropriate. In this respect CT now has the same capability as MRI.

As radiologists become more comfortable with multiplanar imaging, diagnostic accuracy and confidence unquestionably improves. Many diagnoses are much easier to make in nonaxial planes. This can be difficult to fully understand and appreciate until it becomes a routine part

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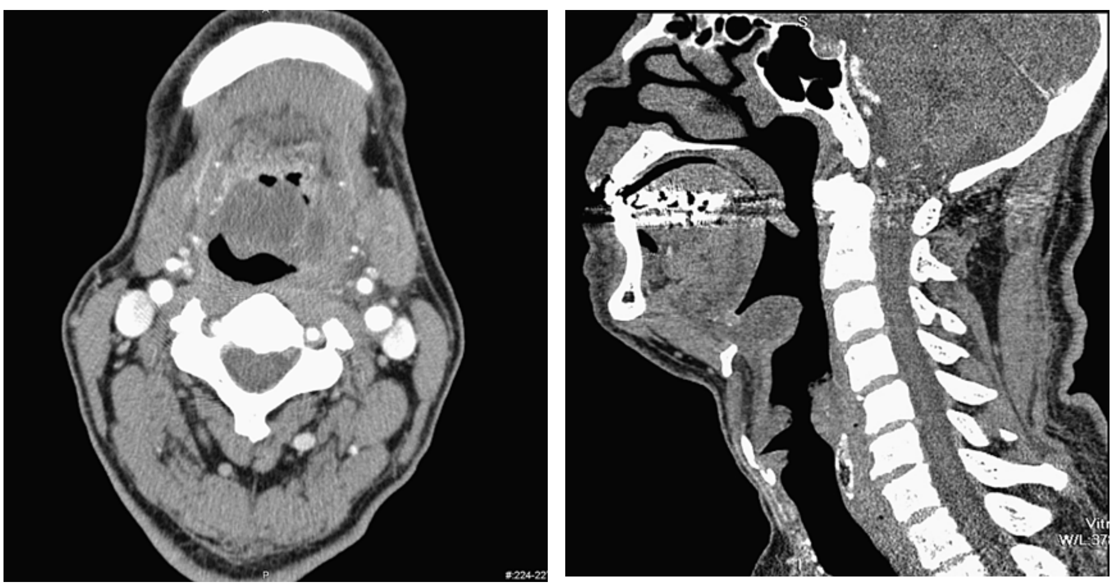
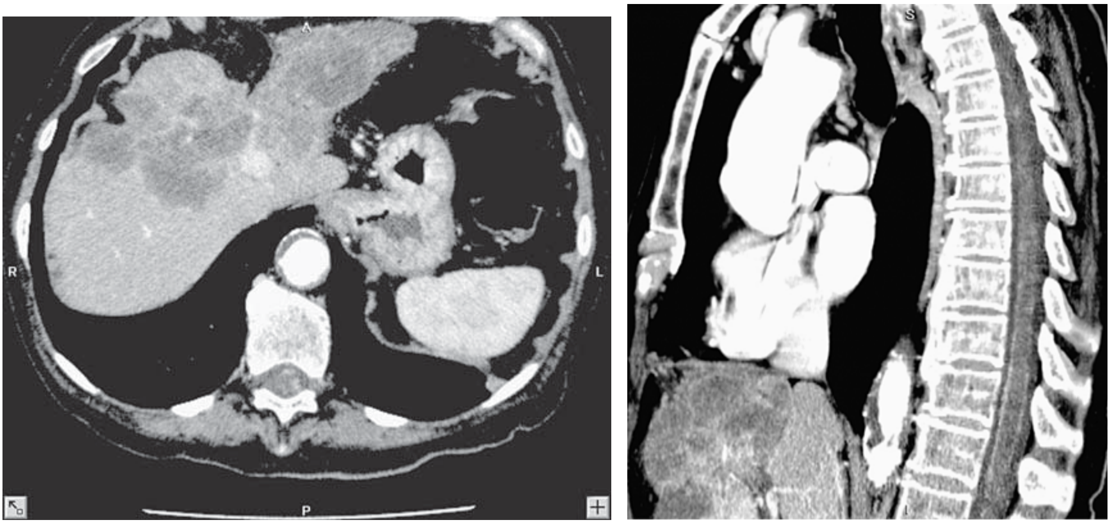


B

Figure 4.3. Acute epiglottitis. (A) Axial 3-mm image of a 25-year-old man having difficulty swallowing, neck pain, and fever. Enlargement of the epiglottis is present on this image but can be easily overlooked on the axial slices. (B) Sagittal reconstruction makes identification of the abnormal epiglottis much easier and more obvious.



A B

Figure 4.4. Leptomeningeal carcinomatosis from breast carcinoma. (A) Axial 3-mm image shows extensive liver metastasis. Nodular enhancement is present on the surface of the spinal cord, but this is very difficult to detect on the axial images. (B) Sagittal reconstruction shows linear and nodular enhancement on the surface of the cord. Findings are less likely to be missed on the sagittal images.

of your practice. Also, with isotropic imaging, any oblique plane can be easily created and reviewed with no loss of image quality.

There is no question that routine review of multiplanar images is beneficial, but there are significant choices to be made as to how they should be created. The two major options are to create the MPRs on the scanner console directly and send them to PACS, or to create the MPRs directly on the PACS system or workstation from the thin section data. Both options have certain advantages and disadvantages.

Scanner-Created MPRs

With current MDCT scanners, creation of sagittal and coronal images on the scanner is easy. The images can be manually created by the technologist or automatically generated by the scanner software and built directly into the examination protocol. Automatically generated reconstructions ensure that the MPRs are always done and are time efficient for the technologist. These images are generally straight sagittal and coronal planes. If oblique images are desired, the technologist generally must create them manually.

For the radiologist, MPR images created by the scanner and sent to PACS have many advantages. Foremost among them is that the images are routinely and immediately available for review. Most modern PACS systems allow the user to display and link multiple sequences at once. This allows the radiologist to quickly and efficiently review and compare images in multiple planes. The most appropriate plane can be chosen for primary review and pathology can be easily correlated into three planes. The process is simple, reliable, and effective.

The main disadvantage of scanner-created MPRs is a lack of flexibility. Radiologists are limited to predetermined reconstruction planes for a given examination. If the radiologist wants to see the images in a nonstandard or oblique plane, he must either ask the technologist to create the desired images on the scanner and send them to PACS, or have the data transferred to a workstation that will allow interactive reconstruction of the data by the radiologist or technologist. In either situation there is some delay and inconvenience in reviewing the case.

PACS/Workstation-Created MPRs

Many PACS systems now allow users to interactively create multiplanar reconstructions directly on the PACS monitor. In the future it is likely that all new systems will have this feature. It is important to remember that to create high-quality reconstructions the thinnest possible slice reconstruction (equal to the thickness the image was acquired at) must be sent to the PACS system or workstation. Since data sets are frequently huge (hundreds or even thousands of images), they have the potential downside of slowing down the network, causing cases to take much longer to load onto PACS, creating cumbersome data sets to review, and increasing storage costs. As networks and computers rapidly improve and get faster, and storage costs fall, these issues will likely become trivial, but at this time this remains an important consideration for many sites that must utilize computers and networks that are less than state of the art.

The main advantage of creating MPRs on PACS or a workstation is the flexibility and interactivity it provides. Radiologists have at their fingertips the ability to create images in any plane. This can be a powerful tool in some cases. The main disadvantage is that this generally requires the radiologist to perform a few extra steps in order to see the MPR images. Even if the time involved is minimal, many radiologists will fail to use this feature routinely and save it for only select cases. Both radiologists and clinicians like to have the images immediately available and accessible. As software continues to improve this will likely cease to be an issue. In the future I suspect all radiologists will have immediate access to multiplanar, volume, and MIP images directly on the PACS system, and the separation between PACS monitors and dedicated 3D workstations will continue to blur. Once this occurs it will no longer be necessary or advantageous to create reconstructions on the scanner console.

Image Review

Effective use of a MDCT scanner requires soft copy image review. Even sites that are unable to install a full PACS system can institute a system to review images on computer at a relatively small cost (film archival and storage is a different story, however). The number of different options for soft copy image review is huge, and a full discussion of PACS systems is beyond the scope of this book. However, there are some general concepts that are widely applicable and worth discussing.

One of the great benefits of soft copy review is the ability to rapidly scroll through large data sets. The transition from a sheet-based review to a scrolling-based review can initially be challenging for some radiologists, but once made is well worth the effort. Gains in efficiency and accuracy can be expected. Pathology is much easier to identify, and there is less fatigue on the eye and mind when images are reviewed in this manner.

Another great benefit of computer-based image review is having an electronic toolset at your fingertips. Almost all systems allow the user to easily window images manually or with presets, measure objects and Hounsfield units, annotate, adjust image sharpness and contrast, and magnify images. Other available features include the ability to easily compare images, check prior reports, link images, and save select images for teaching or conferences. Select image files can also be printed or emailed to referring doctors, and even incorporated directly into the radiology report. Many current PACS systems also include advanced tools such as ones providing the ability to create MPR, volume, or MIP images directly on the PACS. Systems are also available that have all of the functionality of both a PACS monitor and a 3D workstation seamlessly integrated into one unit.

An important and often overlooked part of utilizing PACS effectively is setting up user-friendly hanging protocols. Most systems allow for some degree of customization when setting up protocols. Individual preferences will vary, but when viewing MDCT it is helpful to have each series loaded in a different screen partition for easy scroll review and comparison. If possible, having the sequences automatically linked and cross-referenced is extremely helpful. Cross-referencing allows users to localize findings between axial, sagittal, and coronal images. Linking can allow direct comparison of images pre- and postcontrast or between different window settings. The number of separate partitions the monitor is divided into should vary depending on the number of different series available and whether or not a comparison is being loaded. The downside of having multiple partitions open per monitor is that the image size gets smaller and smaller. This is usually not a significant factor for CT until more than four to six partitions per monitor are used.

Selected Readings

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