CT Image Visualization: A Conceptual Introduction

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Computed tomography (CT) postprocessing produces information-rich diagnostic images, transforming enormous amounts of x-ray attenuation data into clinical information that can assist in diagnosis and treatment. This article briefly reviews the history of the technological evolution of CT imaging equipment and provides a conceptual overview of scan data visualization processes. Trends in and examples of image postprocessing, segmentation, registration and fusion techniques, and computer-aided detection are described. Finally, the uses of these visualization algorithms in selected diagnostic imaging applications are discussed.

Computed tomography (CT) has revolutionized diagnostic imaging and clinical care over the past 4 decades. During that time, incremental and monumental technological advances have yielded dramatic improvements in the precision and amount of data that can be acquired in a single CT examination. To make full use of these larger data sets, improvements in computing power and software design also have been necessary. As Johnson and Fishman explained:

The key to computed tomography imaging in the big picture is not in the acquisition of data, but in the use of the data acquired. Postprocessing of computed tomography data is thus no longer an option, but a true requirement in this era of 64-row multidetector computed tomography and beyond.1

CT imaging uses “data to create knowledge,” they wrote. “It is this knowledge that can improve patient care, through earlier disease detection and accurate diagnosis.”

Once a CT scan is acquired, 3 data processing steps typically are undertaken to transform scan data sets into clinically useful images:

- Registration aligns anatomically overlapping scan data from an examination or aligns scan data from different diagnostic imaging modalities or serial examinations to produce information-rich displays. Multimodality data coregistration, such as that aligning positron emission tomography (PET) and CT image data, is also known as image fusion.
- Visualization involves postprocessing registered data to generate clinically useful images. Many postprocessing techniques

After completing this article, the reader should be able to:
- Summarize the technological innovations in computed tomography (CT) scanner design that led to current rapid scan acquisitions and visualization.
- List and describe common CT visualization techniques.
- Identify the diagnostic imaging applications of different postprocessing techniques.
- Explain the role of ray-casting algorithms in several visualization techniques.
- Describe how improvements in computational power and digital memory capacity have affected common postprocessing practices.
- Discuss the potential clinical roles of Hesse rendering and computer-aided detection visualization algorithms.
can be used individually or in combination to address specific diagnostic questions and confirm clinical signs.

- Segmentation partitions scan data into anatomic features, distinguishing anatomic boundaries or surfaces of interest from adjacent anatomy so the surface contours or internal features of soft tissues, bones, or vasculature can be visualized. Segmentation involves a number of different algorithmic approaches and is increasingly performed automatically, with relatively little manual input from the radiologic technologist. Segmenting scan data dramatically reduces the size of data sets, allowing more efficient assessment of clinically relevant anatomic features. In recent years inexpensive computing power and increased digital storage capacity have reduced the technological barriers to rapid visualization using large scan data sets, and computationally demanding data-rich visualizations are becoming a routine part of radiology practice.

**History**

The CT revolution is arguably the most important advance in medical imaging since the discovery of x-rays in 1895. The conceptual basis for this technological revolution is deceptively simple: x-ray attenuation coefficients allow CT values (expressed as Hounsfield units, HU) to be calculated; the CT values then are used to demonstrate internal anatomy. Using mathematical formulas worked out in the early 1900s, Italian radiologist Alessandro Vallebona developed single-slice radiographic tomography in the 1930s and 1940s by synchronously pivoting the x-ray tube and film in opposite directions around the target anatomy.

But computed tomography emerged only in the early 1970s, in the early stages of the computer microprocessor era. Its clinical implications and promise were quickly recognized; in 1979, Allan M Cormack and Godfrey N Hounsfield were awarded a Nobel Prize in Medicine for their invention of this new diagnostic imaging modality.

By the early 1990s, slip-ring technology and advances in computing power and software design led to the development of volumetric spiral or helical scanners, allowing faster scan acquisition. Scans could now be completed during a breath hold, reducing the frequency of patient movement artifacts. With helical scanning, a single CT slice could be acquired for each gantry rotation. Subsequent technological advances in acquisition and data postprocessing algorithms have progressively reduced the frequency and magnitude of image artifacts caused by tissue movement.

By 1998, multidetector CT technology became available, allowing the simultaneous acquisition of multiple thin sections (≥ 1 mm) of patient anatomy during yet-faster scans. The multidetector CT unit’s x-ray tube is positioned opposite an array of detectors and the fan-shaped x-ray beam passes through the patient during a single, rapid procedure. The resulting overlapping data set represents CT values in volumetric voxels. By 2006, 64-row multidetector CT scanners produced 64 0.6-mm slices in 0.33 seconds. Now 320-row and 640-slice CT scanners are on the market.

Software has improved alongside CT technology, increasing the potential of innovations in scanner design. Sophisticated algorithmic interpolations of CT scan data readily allow very rapid, near-real-time reconstruction, postprocessing, and segmentation of very precise 2-D or 3-D images from any view plane or perspective. Software advances frequently are overlooked because advances in CT equipment design are easy to see, while algorithmic advances are less obvious.

By the early 2000s, PET-CT units acquired anatomical and physiological data simultaneously, producing fused images. Four years later, dual-energy CT was developed. Dual-energy CT involves mounting 2 x-ray tubes and 2 detector arrays at 90° angles to one another, permitting simultaneous scanning with different scan parameters (eg, different kV). New postprocessing algorithms have been developed specifically for dual-energy CT, although these techniques are not described in this article.

We are now in the era of widespread volumetric multidetector CT postprocessing—an age of unprecedented precise anatomic and temporal CT scan data visualization. That precision reflects dramatic gains in the sophistication of software postprocessing tools and techniques—the unseen processes that transform massive data sets of attenuation coefficients into visual representations of a patient’s internal anatomy.
According to Johnson and Fishman:

The information provided by a comprehensive postprocessed study, which includes multiplanar reconstruction in the coronal, sagittal, and oblique plane, as well as 3-Dimensional maps… using volume rendering and maximum intensity projection (MIP) techniques, allows for key clinical decisions to be made with a high degree of accuracy.¹

Workstations, Image Display, and File Sharing

Generally speaking, 3-D images provide realistic views similar to the actual appearance of the intact or dissected anatomy that clinicians use for training.¹⁰ Three-dimensional postprocessing therefore offers the advantage of direct visualization, as well as efficient interpretation and communication, alternative visualizations to address specific clinical questions, and volumetric quantitation.¹⁰

Modern image analysis workstations readily allow the use of postprocessing techniques and rapid switching between different visualization techniques. Storing and transmitting CT data sets typically involves the Digital Imaging and Communications in Medicine (DICOM) standards, allowing comparable gray-scale visualizations on different monitors and the integrated acquisition and sharing of image data in a medical picture archiving and communication system (PACS).¹⁰ Screen shots also can be saved in other common file formats such as JPEG and TIFF.¹,¹⁰

Increasingly, multiplatform software packages are replacing dedicated image processing workstations for 3-D image analysis.¹⁰ Desktop, laptop, and tablet computers now can frequently be networked to share data and images, offering much more versatility than stand-alone workstations.¹⁰

Many contemporary workstations and viewing platforms allow rapid 2-D and 3-D visualization using different techniques, segmentation, registration, computer-aided detection, and image quantitation (eg, on-screen length and diameter measurements).¹¹

Visualization Techniques

To display data digitally, information is presented as a pixel or a voxel. Pixel comes from truncating the term picture element to describe a tiny area on a display screen that is combined with many other pixels to create an image. A voxel (“volumetric pixel”) is the 3-D equivalent of a pixel. Two-dimensional pixels and 3-D voxels tend to be near isotropic; that is, they are the same size in both or all 3 dimensions.⁶ However, voxels also can be acquired anisotropically, with unequal voxel dimensions, such as when height corresponds to the distance between slices (see Figure 1).² When voxels are not acquired as cubes, 3-D image postprocessing quality can be degraded by errors introduced during interpolation calculations.² In contrast, volumetric scanning that yields nearly cubic voxels allows more reliable and precise visualization of complex anatomy along multiple axes.² Near-isotropic data sets therefore can be more readily postprocessed using different algorithms to generate task-specific visualizations. This has hastened the development of new CT applications, such as CT angiography and CT colonography.⁶

However, despite these improvements, visualization artifacts and ambiguities still occur in modern postprocessed images. Postprocessing algorithms are extremely complex, and peculiarities are to be expected. Manual or interactive control of postprocessing parameters, as opposed to fully automated postprocessing, also introduces variation to the process.

Planar (eg, axial 2-D) images should be provided or made readily retrievable by the radiologist alongside postprocessed 3-D reconstructions, allowing him or her to refer to the original images when assessing postprocessed visualizations.¹⁰ Modern PACS workstations and image postprocessing platforms offer simplified access to multiple visualizations from a single CT examination. Ready access to multiple visualizations is important because anomalies such as beam hardening, patient motion, and streaking artifacts might be more readily recognized in the planar 2-D images than in 3-D images.¹⁰ Artifacts in volume-rendered images can create the illusion of blood vessel stenosis (lumen narrowing) or occlusion. Such signs must therefore be confirmed by reviewing planar images.¹⁰

Different CT scan data postprocessing techniques can offer clinicians different information and insights about target anatomy. Among the most common postprocessing techniques are multiplanar reconstructions,
curved planar reformations, volume renderings, shaded surface displays, maximum intensity projections (MIPs), minimum intensity projections, and ray-sum or average intensity projections. These methods are not mutually exclusive; each has its own strengths and limitations, and different techniques can yield different insights into the same patient anatomy (see Table).

No one postprocessing technique has been shown to be clearly and consistently superior in all cases. Therefore, the most useful workstation and image display platforms are those that allow rapid visualization using multiple postprocessing techniques to best exploit the strengths of these different techniques. For example, in describing postprocessing in CT angiography, Rubin et al emphasized that:

*The most powerful and effective means of analyzing cardiovascular imaging data is to work within a visualization environment that allows rapid switching between the various visualization methods, allowing for interactive exploration of the data. A formal assessment of the underlying anatomy and pathology is thus made through a composite assessment by using the various available visualization techniques.*

Postprocessing can improve the clinical utility of a CT examination in several ways:

- Flexibility or alternative visualizations — the rapid visualization of outer anatomic surface appearances, organ interiors, or lumens allows clinicians to address specific questions.
- Efficient interpretation — it is frequently said that a picture is worth a thousand words. Similarly, in clinical settings, a single postprocessed image can be worth a thousand 2-D CT slice images. Individually inspecting more than 2000 primary planar 2-D

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**Figure 1.** Schematic representation of anisotropic and isotropic scan acquisitions. A. Anisotropic computed tomography (CT) scan acquisition, adequate for axial 2-D images. B. Anisotropic 16-detector CT acquisition with wide collimation. By overlapping the reconstruction interval, this data set provides excellent reformatted and volume-rendered images for many applications. C. Isotropic 16-detector CT scan acquired with narrow collimation, yielding voxels that are symmetric in all 3 dimensions, “exquisite” for multiplanar and 3-D visualizations. Reprinted with permission from Dalrymple NC, Prasad SR, Freckleton MW, Chintapalli KN. Informatics in radiology (infoRAD): introduction to the language of three-dimensional imaging with multidetector CT. Radiographics. 2005;25(5):1414. doi:10.1148/rg.255055044.
CT reconstructions would require hours of a clinician’s time. But when planar images are presented in a more intuitive 3-D image or a “fly-through” sequence such as those used in virtual endoscopy, the clinically relevant features of a patient’s anatomy can be more quickly and efficiently assessed.

- Volumetric quantitation – many complex anatomic volumes, lengths, diameters, and other geometric relationships are more readily quantified in postprocessed images than primary planar reconstructions.

It should be noted that traditional planar reconstructions should not simply be replaced with postprocessed images and then disregarded. Instead, selected planar images are used to more carefully examine anomalies that appear in postprocessed visualizations. That is, primary and postprocessed images should be examined in combination, rather than one or the other exclusively.

**Multiplanar Reconstructions**

Primary axial slice images can offer useful visualization of specific local details of a region of interest, but they do not always include all clinically relevant anatomic information. For example, planar images of vasculature demonstrate only a small portion of a given blood vessel’s tortuous or complexly twisted pathway through the body. Similarly, axial images of a particular vertebra might not display intervertebral disks or the vertebra’s relationship to adjacent vertebrae. But with multiplanar reconstruction, axial images can be algorithmically “stacked” to reconstruct visualizations in other 2-D planes (eg, coronal, sagittal, or oblique). Multiplanar reconstruction commonly is used to evaluate the spine or other skeletal structures (see Figure 2). For structures that are not orthogonal to the scan, oblique planes can be calculated for visualization.

**Table**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Strength</th>
<th>Limitation</th>
</tr>
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<tbody>
<tr>
<td>Multiplanar reconstruction</td>
<td>Identifies stenosis, occlusion, calcification, and stents</td>
<td>Limited visualization of spatial relationships and curved blood vessels</td>
</tr>
<tr>
<td>Curved planar reformation</td>
<td>Identifies stenosis, occlusion, calcification, and stents</td>
<td>Distortion of extravascular structures when centered on a blood vessel; branch vessels poorly visualized</td>
</tr>
<tr>
<td>Maximum intensity projection</td>
<td>Depicts small, branch, and poorly enhancing blood vessels</td>
<td>No quantitation of blood vessel dimensions; high-attenuation voxels such as calcifications obscure vascular lumen</td>
</tr>
<tr>
<td>Volume rendering</td>
<td>Excellent visualization of complex spatial relationships</td>
<td>No quantitation of blood vessel dimensions</td>
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**Figure 2.** Multiplanar reformation. A. Coronal reformatted image from a routine abdominopelvic CT scan. B. Sagittal formatted image produced from CT data acquired with a trauma protocol of the chest, abdomen, and pelvis. Reprinted with permission from Dalrymple NC, Prasad SR, Freckleton MW, Chintapalli KN. Informatics in radiology (infoRAD): introduction to the language of three-dimensional imaging with multidetector CT. Radiographics. 2005;25(5):1416. doi:10.1148/rg.255055044.
Curved Planar Reformations

Curved planar reformation images are essentially multiplanar reconstructions that display, in cross-section, the long axis of particular anatomy, such as a blood vessel or stretch of the digestive tract (see Figure 3). Curved planar reformations can demonstrate the entire length of the target tissue in a single image for efficient assessment of lumen stenosis, occlusion, or obstruction, for example.

Ray Casting

Ray-casting algorithms are used to create 2-D representations of underlying volumetric scan data. These calculations project a linear ray of imaginary light through voxel data from a scanned volume, noting the x-ray attenuation values (HU) for each voxel encountered at sampling points along its path (see Figure 4). At each sampling point, voxels are assigned brightness values that reflect attenuation coefficients. The brightness of pixels in the resulting 2-D projections reflect calculations based on the underlying volume’s attenuation values encountered by the cast ray at all sampling points.

Using ray-casting algorithms, several composite projections can be visualized, usually in 2-D images. In recent years, it has become possible to project these composited projections onto 3-D surface renderings. Importantly, whether ray casting–based projections are presented as 2-D or 3-D images, depth-distance relationships of the underlying anatomy are not represented in the projections.

Several projection techniques use ray casting:

- Maximum intensity projections – are generated using only the highest attenuation values encountered along each ray path (see Figure 5). This technique is used to show bone and contrast-filled anatomy, such as cardiac vessels. MIP images retain only the highest gray-scale values and therefore typically represent 10% or less of the volumetric scan data from which they are derived.

- Average intensity projections – represent the average attenuation along an entire ray path through the specified scan volume (see Figure 6). A similar, alternative algorithm is ray-sum projection, which

Figure 3. Curved planar reformation. A. Three-dimensional volume-rendered image shows the curved course of the right coronary artery. B. Curved planar image of the right coronary artery shows a cross-section of the vessel in its entirety. In this case, several points were selected along the course of the vessel on axial images; semi-automated software then defined an imaging plane that includes the entire length of the vessel. Because the imaging plane is defined by the vessel, other structures in the image are distorted. Reprinted with permission from Dalrymple NC, Prasad SR, Freckleton MW, Chintapalli KN. Informatics in radiology (infoRAD): introduction to the language of three-dimensional imaging with multidetector CT. Radiographics. 2005;25(5):1417. doi:10.1148/rg.255055044.
adds the total of all voxel attenuation values encountered along the ray path. Average intensity projections and ray-sum projections are visually similar.

- Minimum intensity projections – depict only the lowest attenuation values for each ray path (see Figure 7). This is sometimes used to visualize the large airways of the lungs and regions of suspected air trapping that occur in progressive lung diseases such as emphysema (see Figure 8).

### Shaded Surface Displays and Volume Rendering

Scan data also can be used to produce 3-D image reconstructions that can be presented from multiple view angles or anatomic perspectives, such as volume and surface renderings. Three-dimensional displays appear and can depict an entire organ or volume of interest in a single image. They also improve detection of diagnostic signs or details and can be rotated freely around an arbitrary point or plane of interest. These realistic images are useful in diagnosis, tumor screening, and surgical planning.

Shaded surface display images, also known as surface renderings, present only the surface contours of an anatomy of interest, rather than the cross-sectional visualizations produced by multiplanar reconstruction, curved planar reformation, and projection algorithms. In shaded surface display, segmentation edge-detection and gray-scale thresholding algorithms remove extraneous tissues within the scanned data set. This means that data for underlying, nonsurface portions of a scan volume are discarded (see Figure 9). Cross-sectional visualizations are therefore not an option in shaded surface display as they are with volume rendering.

In shaded surface display, a wire-frame model of the anatomic surfaces is calculated using 2-D “primitives”—distorted geometric shapes such as triangles or polygons—to map segmented surface contours. Gray-scale shading and artificial lighting effects then are added to the resulting, crude surface-contour scaffolding to yield a realistically textured 3-D appearance. Surfaces at a 90° angle to the artificial light source appear brightly lit, while other surface regions are shaded to varying degrees to create the illusion of texture and depth.
Figure 6. Average intensity projection of data encountered by a ray traced through the object of interest to the viewer. The included data contain attenuation information ranging from that of air (black) to that of contrast media and bone (white). Average intensity projection uses the mean (average) attenuation for all values encountered along the ray path to calculate the projected or visualized pixel’s gray-scale value. Reprinted with permission from Dalrymple NC, Prasad SR, Freckleton MW, Chintapalli KN. Informatics in radiology (infoRAD): introduction to the language of three-dimensional imaging with multidetector CT. Radiographics. 2005;25(S):1417. doi:10.1148/rg.25S05S044.

Figure 7. Minimum intensity projection of data encountered along a ray traced through the object of interest to the viewer. The included data contain attenuation information ranging from that of air (black) to contrast media and bone (white). Minimum intensity projection displays only the lowest HU value encountered along the ray path. Reprinted with permission from Dalrymple NC, Prasad SR, Freckleton MW, Chintapalli KN. Informatics in radiology (infoRAD): introduction to the language of three-dimensional imaging with multidetector CT. Radiographics. 2005;25(S):1420. doi:10.1148/rg.25S05S044.

Figure 8. Coronal image of the thorax (slab thickness = 20 mm) created using minimum, average, and maximum projections. A. On the minimum intensity projection image, the central airways are demonstrated clearly. Asymmetric emphysematous changes are seen in the right upper lobe. B. On the average intensity projection image, the central airways are not as well visualized; emphysematous changes remain visible but are not as clear. However, interstitial and pulmonary vascular structures within the lungs are seen better than on the minimum intensity projection image. C. On the MIP image, the airways and emphysematous changes are obscured by vascular and soft-tissue structures, but longer segments of blood vessels are visible than with the average intensity projection image. Reprinted with permission from Dalrymple NC, Prasad SR, Freckleton MW, Chintapalli KN. Informatics in radiology (infoRAD): introduction to the language of three-dimensional imaging with multidetector CT. Radiographics. 2005;25(S):1420. doi:10.1148/rg.25S05S044.
Volume rendering uses artificial lighting and shading effects similar to those used in shaded surface display but only after color and opacity assignments have been made based on voxel percentages. This improves the visual differentiation of tissue types, such as bone and vasculature (see Figure 10). The resulting depictions of depth and surface texture are more intuitively realistic than is possible with shaded surface display, even though volume rendering color assignments do not necessarily reflect real-world tissue colors. However, when colors do emulate real-world anatomy, the images can be strikingly realistic.
photorealistic. It is important to note that calculation errors can yield incorrect color assignments for some tissue types.\textsuperscript{8,10}

In volume rendering postprocessing, each tissue type is assigned an arbitrary color and opacity value, and each voxel’s final color and transparency reflect these assignments, weighted by that voxel’s percentage value.\textsuperscript{11} Therefore, if soft tissue is assigned the color red and bone is assigned white, voxels calculated at 75% soft tissue and 25% bone would appear pink.\textsuperscript{13} And if soft tissue is assigned a 50% opacity (50% transparency) value and bone is assigned 25% opacity, then those pink voxels will appear between 25% and 50% opaque (see Figure 11).\textsuperscript{13}

Volume rendering voxel opacity assignments range from 0% (completely transparent) to 100%.\textsuperscript{10} These percentages are known as opacity transfer functions. Ray casting through the volume samples opacity values at intervals along each ray path. Opacity “ramps” are calculated and consist of 3 zones: a transparent zone, a transitional zone, and a plateau (see Figure 12).\textsuperscript{8,10} Steeper transition zones accentuate anatomic edges.\textsuperscript{8,10} When the transition zone is vertical, the percentage gradation value of volume rendering is lost and images appear like shaded surface displays, with binary all-or-nothing (opaque/not opaque) visualization.\textsuperscript{10} Opacity transfer functions also are used to create volume rendering views of vessels’ interior walls.\textsuperscript{10}

After opacity and color assignments are made, volume rendering postprocessing assigns imaginary-source lighting effects that depict reflections and shading. In volume rendering, the imaginary light source usually is set as the viewpoint.\textsuperscript{10} However, other light sources can be used to emphasize surface anomalies.\textsuperscript{10} Lighting controls are referred to as brightness, contrast, and ambient light settings.\textsuperscript{10}

Volume rendering is an art as well as a science. Different vendors’ software can yield various appearances in the final image because programs use different algorithmic details, and volume rendering algorithms therefore tend to have unique quirks.\textsuperscript{10} In addition, volume rendering postprocessing requires manual or interactive adjustment of display parameters such as the range of opacity values. This can lead to interobserver differences in the resulting images, which can complicate or slow detection of changes in image series acquired at different times.\textsuperscript{13} Display parameters should be documented carefully to ensure consistent interexamination volume rendering postprocessing.\textsuperscript{13}

Figure 11. Schematic diagram illustrating 3-D volume-rendered postprocessing and 2-D MIP postprocessing principles. A. Volume rendering clearly defines individual arteries. B. MIP reconstruction using the same volume scan data set shows all the vessels, but outlines merge as the resulting image is compressed into 2 dimensions, such that spatial relationships between vessels are lost in the final image. Depth information within the imaged volume is lost in MIP postprocessing. Reprinted with permission from Fishman EK, Ney DR, Heath DG, Corl FM, Horton KM, Johnson PT. Volume rendering versus maximum intensity projection in CT angiography: what works best, when, and why. Radiographics. 2006;26(3):909.
Volume rendering is the most demanding postprocessing method in terms of computations and file storage, but advances in computer processor speeds and local and cloud storage have made it a viable routine technique in most clinical settings. Because volume rendering does not involve extensive segmentation and retains most or all scan data for both surface features and adjacent and underlying structures, this postprocessing technique also can yield combination visualizations that depict both realistic surface contours and cross-sectional features (see Figure 11).  

**Hesse Volume Rendering**

When tissues have very similar x-ray attenuation values, color assignment based on attenuation alone is likely to obscure important anatomic features, mistakenly depicting adjacent, separate tissue types as a single structure or tissue type. For example, pulmonary nodules and lymph nodes, which are of interest in lung cancer screening, can sometimes be assigned the same colors in volume rendering.

One potential solution to this problem is Hesse rendering. Hesse volume rendering uses eigenvalue calculations to visualize data about anatomic shapes, rather than gray-scale values to assign colors to the postprocessed visualization. By sampling voxel regions to identify complex local surface contours, rather than individual voxels in isolation, Hesse volume rendering postprocessing differentiates and draws attention to structures of interest, such as polyps, in a manner similar to automated computer-assisted polyp detection functions in CT colonography.

Hesse volume rendering is used as an additional complementary visualization algorithm and is not used in lieu of axial section or volume rendering image reviews (see Figure 13). Non-Hesse volume rendering is sometimes referred to as “direct” volume rendering in the literature on Hesse postprocessing to differentiate between the techniques.

**Perspective Volume Rendering and Virtual Endoscopy**

Perspective volume rendering is used to depict the internal surfaces of lumens, such as the respiratory tract, blood vessels, the colon and intestines, or urinary tract. Perspective volume rendering incorporates a horizon, with close structures appearing larger and distant anatomy appearing smaller. Perspective volume rendering allows not only visualization of the interior lumen wall but also underlying or adjacent anatomy and structures, such as the depth of penetration of a polyp in an intestinal wall—potentially important information for the noninvasive differentiation of low- and high-risk polyps.

Virtual endoscopy refers to the visualization of the inner surfaces of anatomic cavities or lumens using sequential perspective volume rendering images. Virtual endoscopy allows noninvasive emulation of invasive endoscopic procedures. Rapid sequential “fly-through” display of perspective volume rendering images simulates the view through an endoscope that is being advanced into a body cavity. Virtual endoscopy also can depict the colon’s interior lumen surface in a “dissected” or “filet” rendering in which the lumen has been unfolded to a relatively flat-surface visualization of the lumen interior.

**Tumor Texture Analysis**

Advances in surface postprocessing have yielded a new tool that might prove useful for grading and post-treatment monitoring of tumors. CT tumor surface texture analysis has shown early promise in small and preliminary studies at predicting tumor response to treatment and patient survival rates. Texture analysis postprocessing with TexRAD software (Feedback PLC) involves quantifying tumors’ mean gray level intensity, histographic uniformity, kurtosis (“peakedness” or

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**Figure 12.** Linear opacity ramp schematic depicting the visualization of opacity values in volume rendering postprocessing. Opacity ramps define 3 distinct zones: 0% opacity (100% transparency); transition zone; and opacity plateau, in this case, defined as 40% opacity. Reprinted with permission from Rubin GD, Sedati P, Wei JL. Postprocessing and data analysis. In: Rubin GD, Rojsky NM, eds. CT and MR Angiography: Comprehensive Vascular Assessment. Philadelphia, PA: Wolters Kluwer Health; 2009:216.
Independent of tumor size, these early studies’ findings suggest that tumor texture analysis predicts brain cancer grade and patient survival following chemotherapy for squamous cell carcinomas of the head and neck. However, larger controlled clinical studies are needed to confirm these early findings.

Segmentation
Computer processing power and memory storage capacities are increasing dramatically, and the per-unit cost is dropping. As a result, CT scan data set file sizes are not the limiting factor in postprocessing and visualization that they once were, reducing the need for some

Figure 13. Hesse rendering—MIP vs Hesse rendering-direct volume rendering. A. Standard volume rendering image of a 10-cm-thick coronal slab without prior lung segmentation. B. Direct volume rendering image with Hesse color coding. C. MIP image of the 10-cm-thick slab, which is not useful because most of the lung area is occluded by the lung walls. D. MIP image with Hesse color coding (Hessian eigenvalues). Although no prior lung segmentation was used, noncurved structures do not show up in the rendering; thus, the lung walls do not occlude the view. Reprinted with permission from Wiemker R, Dharaiya ED, Bülow T. Informatics in radiology: Hesse rendering for computer-aided visualization and analysis of anomalies at chest CT and breast MR imaging. Radiographics. 2012;32(1):295. doi:10.1148/rg.321105076.
segmentation applications. For example, shaded surface display is quickly being replaced by volume rendering images because the latter technique allows far more rapid and flexible visualization using the entire reconstructed scanned-volume data set. In addition, volume rendering opacity value assignments can be used for image segmentation by assigning an opacity threshold below which image data is omitted from the data set (see Figure 14).

Nevertheless, segmentation plays an important continuing role in removing visual ambiguities from some postprocessed images, and it allows important quantitative measurements of target anatomy. For example, when adjacent anatomy has similar attenuation values, interpretation can be challenging. When only one such anatomic structure is clinically relevant, segmentation offers a solution to this problem. It preserves data for target anatomy within a scanned volume while removing data for nontarget adjacent and background structures. Segmentation reduces the data set size, removes clinically irrelevant visual clutter from the final images, and allows clearer visualization and measurement.

Figure 14. Use of opacity threshold for segmentation, as shown on a full field of view 3-D volume-rendered image of the chest and abdomen. Low opacity threshold allows the skin to obscure the abdominal contents (A) and demonstrate a vertical row of shirt buttons along the patient’s midline. Progressively increasing the opacity threshold excludes first low-opacity tissues such as skin and fat (B); then high-opacity soft tissues such as muscle and bowel wall (C); while contrast-enhanced organs and blood vessels remain (D). Finally, only the most opaque objects (bone, calcium, and excreted contrast material) remain visible (E). Reprinted with permission from Dalrymple NC, Prasad SR, Freckleton MW, Chintapalli KN. Informatics in radiology (infoRAD): introduction to the language of three-dimensional imaging with multidetector CT. Radiographics. 2005;25(5):1426. doi:10.1148/rg.255055044.
example, the heart can be isolated for visualization by removing overlying and surrounding bone and other extraneous tissues.10

Segmentation tools range from manual, user-directed onscreen workstation image-manipulation functions to highly automated processes. Manual segmentation functions include at their simplest the 2-D anterior, posterior, superior, inferior, right or left "cut plane" functions, which less completely extract anatomic details than do more advanced segmentation algorithms, but which nevertheless frequently suffice for diagnostic imaging purposes.10 Oblique cut planes can be recalculated at any angle through an imaging volume to reveal additional anatomic details.10 Other segmentation functions are more complex; these include region-of-interest and region-growing selection tools, all of which allow a workstation user to highlight and include or exclude a particular portion of the scan volume.10 Unlike flat-cut planes, region-of-interest–based tools allow selection of complex anatomic contours, such as the paths of blood vessels.10 Manual "region growing" selection tools allow workstation users to pinpoint a particular structure to be included or removed from the visualization; user-defined upper or lower attenuation values are used to delete or retain adjacent voxels.10,19

More automated processes that require less time and user input also are increasingly common.10 For example, single-click workstation automations now are available for segmenting anatomy of interest, including bone, chest wall, and cardiovascular anatomy.10 This is made possible in part by edge-detection algorithms.19

Because most commercial workstations’ and software packages’ manual and automated segmentation functions are proprietary, algorithmic approaches vary among manufacturers, and evidence-based reviews that pool data from well-designed studies are difficult to perform.10 Postprocessed visualizations always should be interpreted with caution, and clinicians must be aware that postprocessing can inadvertently introduce artifacts or remove anatomic features of interest.10

**Image Registration and Fusion**

Sequential and multimodality diagnostic imaging and the development of imaging-guided medical interventions have all contributed to the need to develop ways to precisely match, or register, a patient’s anatomy on different images, sometimes in near real time.2 The multimodality fusion, or coregistration, of 3-D data sets from CT, magnetic resonance imaging, single photon emission CT, and PET was first developed in the 1980s and 1990s based on feature matching.2 Iterative closest point registration allows registration of anatomic lines and surface contours identified in 3-D data sets. Other registration techniques involve voxel gray-scale value matching.2

Like segmentation, registration processes can be performed manually, with various degrees of semiautomation, or as automated algorithms.2 For example, some semiautomated algorithms involve user approval or rejection of suggested registrations.2 PET-CT image acquisition occurs with the patient in the same position, nearly simultaneously, easing image coregistration. PET-CT examinations yield on-screen displays that show CT images, PET images, and fused images with both anatomic (CT) and physiologic (PET) data depicted.20

**Computer-Aided Detection**

Similar to Hesse volume rendering, algorithms created by the developing field of computer-aided detection (CAD) flag suspicious morphologies that might indicate pathologies, such as tumors or precancerous polyps. CAD programs are not intended to provide definitive diagnoses but rather to communicate to a radiologist, “Do not overlook this.” Many detection algorithms are based on imaging features associated with confirmed pathologies identified through massive PACS data mining projects.11 CAD polyp detection in CT colonography uses Gaussian curvature to spot the mushroomlike shape of some high-risk polyps, and automatically assigns them a color to flag them for closer visual assessment.11,15,21 Edge-preserving smoothing algorithms have allowed significant CT radiation dose reductions without losing the ability to identify suspicious polyps on the colon lumen wall.11

Similarly, researchers have developed algorithms for the automated detection and quantification of pulmonary tumors, and validation studies have shown, not surprisingly, that CAD performance depends on the spatial resolution of postprocessed images.21,22 CAD
algorithms for detecting pulmonary emboli and pneumothorax in multidetector CT data sets, liver tumor boundaries, and calcified cardiovascular plaques are also under development.\textsuperscript{11,21}

**Select Clinical Applications of Postprocessing Techniques**

CT’s superior resolution and advances in postprocessing are rapidly moving the modality beyond its origins in visualizing only large vessels and bones to important new roles in cardiovascular, pulmonary, colon, and musculoskeletal imaging.\textsuperscript{2,13}

**Bone Fractures**

Bone fractures are commonly caused by trauma and by bone loss or tumors.\textsuperscript{24} Excluding or identifying and assessing bone fractures was the first application of 3-D CT image postprocessing and remains one of the most common applications for 3-D CT imaging, which offers significantly improved image detail and accuracy over traditional trauma radiography.\textsuperscript{14,25} Facial fractures can be complex and frequently are accompanied by other forms of trauma that might not be immediately apparent during the patient’s clinical examination.\textsuperscript{26}

Multiple trauma requires rapid diagnostic imaging as soon as the patient is stabilized to thoroughly assess the extent and nature of bone fractures and other traumatic injuries.\textsuperscript{29} Multidetector CT imaging can offer a single rapid, detailed imaging examination to show different bones and tissue types.\textsuperscript{35} Spinal trauma imaging is indicated for all trauma patients because it is crucial to identify and determine the extent and stability of spinal fractures, and because spine injuries can be missed during initial clinical examinations.\textsuperscript{35}

The most common techniques of bone CT postprocessing are MIP, shaded surface display, and volume rendering.\textsuperscript{14,25} MIP images depict only the highest-intensity anatomies encountered along a given ray projection.\textsuperscript{25} Shaded surface and volume rendering offer a “real world” visualization of bone surfaces with overlying soft tissues and vasculature removed. Volume rendering is more accurate than shaded surface display because of its depiction of voxels that contain only a small proportion of bone tissue. It can therefore depict the cortical or hard-bone fragments or components in overlying and subcortical bone tissues.\textsuperscript{24} Volume rendering can visualize bone as shaded, unshaded, or oblique-shaded to detail surface and underlying anatomies.\textsuperscript{24} Unshaded volume-rendered images look like plain radiographs and have fewer artifacts than the other techniques.\textsuperscript{24}

Three-dimensional CT images are used in assessing fracture displacement and in surgical planning in complex anatomic regions such as the spine, hip, and other joints. The 3-D CT images help with surgical planning when, for example, the optimal placement of metal fixation implants (eg, screws) must be identified.\textsuperscript{24} Complex fractures can be readily seen with surface shading, but surface-shaded display images sometimes fail to represent “minimally displaced” fractures underneath the outer cortical bone layer.\textsuperscript{24} Volume rendering is preferred for the detection and assessment of such small fractures, and it can better demonstrate “complex injuries and complicated spatial information about the relative positions of fracture fragments.”\textsuperscript{24} Therefore, suspected spinal cord injury is an indication for volume rendering, in part to identify bone fragments, fractures, and displacement or damage to intervertebral discs.\textsuperscript{25}

Volume rendering sensitively detects and details fractures in the ribs, scapula, and sternum.\textsuperscript{25} Rib and sternum fractures are common chest injuries in multiple trauma patients, and they are easily missed on chest radiographs.\textsuperscript{25} Scapula fractures likewise are easily missed on radiographs.\textsuperscript{25}

Two-dimensional and 3-D postprocessing also are useful to identify fractures in the bones of the arms, wrists, hands, legs, knees, ankles, and feet.\textsuperscript{25} Volume rendering of complex fractures involving joints yields far more clinically useful images than conventional radiography because volume-rendered images detail the extent and stability of those fractures, as well as the articulating surfaces of component bones, allowing their detailed description and classification.\textsuperscript{25}

Pelvic fractures usually are caused by trauma and frequently are associated with severe hemorrhage.\textsuperscript{23} When vascular injury or emergencies such as a hemorrhage are suspected after trauma resulting in bone fractures, intravenous contrast CT angiography can be performed for concurrent MIP-postprocessed visualization of bone fractures and associated blood vessels.\textsuperscript{24}
**Cardiovascular Assessment**

CT cardiovascular postprocessing tools improve the precision and clarity of visualizations and allow quantification of blood vessel stenosis and occlusion. Since the advent of multidetector CT imaging, CT angiography has become a routine and “key component of state-of-the-art imaging,” with roles in tumor staging and assessment of coronary and peripheral artery disease, aortic aneurysms, and cardiac function. Automated and semiautomated algorithms are now widely available for vasculature segmentation, stenosis quantification, and blood vessel tracking.

Multiplanar reconstructions can be used to assess the cardiac chambers, but it can demonstrate only short segments of tortuous arteries. Curved planar reformations can be used instead to assess stenosis in the coronary and pulmonary arteries; however, only one vessel can be visualized in an image, and branch vessels are not typically visible.

Two postprocessing techniques are now in wide use with CT angiography: MIP and volume rendering. Each has strengths and weaknesses. For example, MIP images are subject to artifacts near high-attenuation voxels that distort visualization of blood vessel lumens. Therefore, MIP is not a reliable technique for visualizing vasculature adjacent to calcified atherosclerotic lesions. MIP images also do not visualize the depth relationships of anatomic structures. This can cause overlap between bone, calcifications, and intravenous contrast media on the image and could require segmentation (elimination) of bone to reveal vascular details, for example. Small, tortuous blood vessels might be only partially or intermittently visualized within the scanned volume, creating visualization anomalies such as the “string of beads” artifact, with each “bead” representing a portion of the vessel that fell within the target volume, and gaps representing lengths of the vessel that fell outside the target volume. And because MIP visualizes only the highest attenuation values encountered during ray casting, adequate contrast enhancement is crucial. Finally, MIP does not differentiate soft tissues well.

Volume rendering postprocessing, in contrast, demonstrates different tissue types and anatomic relationships in more detail, is less prone to calcification-associated distortions, and can be used more reliably to grade vascular stenosis. The primary goal of volume rendering opacity transfer function sampling in CT angiography is to visually isolate contrast-enhanced blood vessels from other anatomy. Volume rendering also allows luminal views of blood vessels’ interior walls. However, volume rendering images do not typically visualize smaller branch vessels as readily as do MIP images.

**Pulmonary Assessment**

Detailed imaging of the airways and supportive lung parenchymal tissues has improved dramatically since the introduction of multidetector CT. Curved planar reformation visualizations allow:

- Analysis of pulmonary vasculature and airways.
- Confirmation of airway diameters and narrowing.
- Correlation with functional respiratory testing evidence of airflow limitation such as forced expiratory volume in 1 second (FEV1).

Sagittal multiplanar reconstruction visualization of the lungs can be used to confirm diffuse lung disease. MIP visualization can be useful in the detection and initial evaluation of lung nodules, such as possible lung tumors. MIP also is useful for differentiating in-airway air from subtle diffuse ground-glass opacities in the lungs—an increased attenuation in lung parenchyma that does not involve local airways and which can be a sign of interstitial lung disease. Minimum intensity projection visualization can help identify regions of trapped air associated with progressive chronic lung diseases such as emphysema and chronic obstructive pulmonary disease. In addition, small airway disease can be identified with minimum intensity projection images, which enhance attenuation contrast across lung regions.

The National Emphysema Treatment Trial found that the distribution of emphysema within the lungs is predictive of patient outcomes after lung reduction surgery. Pulmonary CT to assess the extent of emphysema can be conducted with multiplanar reconstruction and volume rendering visualization, but clinical trials have not yet established whether these techniques are better than standard transverse CT. Multiplanar reconstruction and 3-D virtual
bronchoscopic imaging offer guidance for minimally invasive transbronchial needle aspiration and lymph node biopsy procedures, and they are valuable in surgical planning of bronchopleural fistula and bronchoscopic lung volume reduction in patients with advanced emphysema.12

CAD of chronic pulmonary diseases (eg, chronic obstructive pulmonary disease and occupational interstitial lung disease) has not yet come into widespread clinical use.9 However, CAD algorithms for detecting pulmonary emboli are in development.9

The Future of CT Postprocessing

With increasing computer processing power, the sophistication, specificity, and speed of postprocessing algorithms have improved drastically and should continue to improve in years to come. Postprocessing software has yielded an increasing arsenal of applications for interpreting CT scan data.13 Faster algorithms, novel applications, and a growing array of devices on which postprocessed 3-D images can be viewed and interpreted, including smartphones and tablet computers, promise to hasten the CT revolution in medical imaging.13 Fusing multimodality image data sets and generating postprocessed CT images in near real time is likely to play an increasingly important role in diagnostic imaging and image-guided surgery.7 As CT data sets and advanced postprocessing algorithms offer even more precise visualizations of patient anatomy, new applications likely will emerge and existing applications will become more reliable. For example, CAD algorithms likely will become more sophisticated, accurate, and clinically useful in an expanding array of settings. More precise surface visualizations and shape-detecting algorithms, such as the Hesse color rendering and tumor surface texture analysis algorithms, might allow increasingly sophisticated noninvasive diagnostic and prognostic imaging.14

Increasing automation is also a common theme in registration, segmentation, and CAD of potential pathologies in CT data sets. This trend will continue, but it is unlikely to ever become error free. It will remain crucially important to visually inspect postprocessed images carefully, rather than relying entirely on the algorithms that produce them.


1. Transforming computed tomography (CT) scan data sets into clinically useful information typically involves:
   1. registration.
   2. visualization.
   3. segmentation.
   a. 1 and 2
   b. 1 and 3
   c. 2 and 3
   d. 1, 2, and 3

2. We are now in the era of widespread ______ postprocessing.
   a. helical CT
   b. multidetector CT
   c. dual-energy CT
   d. fusion

3. No one postprocessing technique has been shown to be clearly and consistently superior in all cases.
   a. true
   b. false

4. Postprocessing can improve the clinical utility of a CT examination in which of the following ways?
   1. alternative visualizations
   2. efficient interpretation
   3. volumetric quantitation
   a. 1 and 2
   b. 1 and 3
   c. 2 and 3
   d. 1, 2, and 3

continued on next page
5. _____ commonly is used for evaluating the spine or other skeletal structures.
   a. Multiplanar reconstruction
   b. Curved planar reformation
   c. Maximum intensity projection (MIP)
   d. Perspective volume rendering

6. _____ visualizes the long axis of a particular anatomy in cross-section.
   a. Multiplanar reconstruction
   b. Curved planar reformation
   c. MIP
   d. Perspective volume rendering

7. Ray-casting algorithms are used to create 2-D representations of underlying volumetric scan data.
   a. true
   b. false

8. Ray-casting algorithms are used in which of the following?
   a. multiplanar reconstruction
   b. curved planar reformation
   c. MIP
   d. perspective volume rendering

9. Shaded surface display images, also known as surface renderings, present only the surface contours of an anatomy of interest.
   a. true
   b. false

10. What are “primitives”?
    a. antiquated single-detector CT designs
    b. distorted geometric shapes such as triangles
    c. attenuation values underlying composited pixels
    d. outdated segmentation practices in 3-D visualizations

11. Because _____ postprocessing assignments are binary, the extent and size of visualized bone fractures are not always accurate.
    a. MIP
    b. curved planar reformation
    c. shaded surface display
    d. volume rendering

12. Volume rendering voxel opacity values can range from 0% to _____ %.
    a. 85
    b. 90
    c. 95
    d. 100

13. Opacity transfer functions are used to create volume rendering views of vessels’:
    a. interior walls.
    b. exterior walls.
    c. lumen.
    d. blood flow.

14. Which is the most demanding postprocessing method in terms of computations and file-storage memory?
    a. MIP
    b. curved planar reformation
    c. shaded surface display
    d. volume rendering

15. Which of the following can depict both realistic surface contours and anatomic cross-sections?
    a. MIP
    b. curved planar reformations
    c. shaded surface display
    d. volume rendering

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16. Color assignments made on the basis of ______ alone can mistakenly depict adjacent separate tissue types as part of a single structure or tissue type.
   a. attenuation values
   b. opacity values
   c. eigenvalue calculations
   d. surface textures

17. Hesse volume rendering uses:
   a. attenuation values.
   b. opacity values.
   c. eigenvalue calculations.
   d. surface textures.

18. ______ provides a distance horizon, with near anatomy appearing larger and more distant structures appearing smaller.
   a. Multiplanar reconstruction
   b. Curved planar reformatting
   c. MIP
   d. Perspective volume rendering

19. Virtual endoscopy involves visualizing anatomic cavities using sequential ______ images.
   a. multiplanar reconstruction
   b. curved planar reformatting
   c. MIP
   d. perspective volume rendering

20. Recent studies suggest that CT tumor surface texture analysis may be used to predict:
   1. tumor diameter.
   2. tumor response to treatment.
   3. patient survival rates.
   a. 1 and 2
   b. 1 and 3
   c. 2 and 3
   d. 1, 2, and 3

21. Volume rendering ______ assignments can be used in image segmentation.
   a. attenuation value
   b. opacity value
   c. eigenvalue calculation
   d. surface texture

22. Multimodality coregistration or fusion can be undertaken with CT plus all of the following **except** ______ images.
   a. single photon emission CT
   b. magnetic resonance
   c. positron emission tomography
   d. ultrasonography

23. Computer-aided detection validation studies emphasize the importance of the ______ of postprocessed images.
   a. spatial resolution
   b. opacity assignments
   c. color parameters
   d. light source viewpoint

24. Which 2 postprocessing techniques are widely used with CT angiography?
   a. curved planar reformatting and MIP
   b. perspective volume rendering and curved planar reformatting
   c. MIP and volume rendering
   d. multiplanar reconstruction and volume rendering

25. Which type of CT visualization can help identify regions of trapped air associated with emphysema and chronic obstructive pulmonary disease?
   a. MIP
   b. minimum intensity projection
   c. average intensity projection
   d. volume rendering
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