Three Dimensional Imaging of Computed Tomography: Techniques and Applications

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Abstract
The newer imaging modalities, such as Computed Tomography and Magnetic Resonance Imaging, have resulted in a large increase in the amount of information available to the Radiologist, with subsequent improvement in diagnostic performance. 3D Imaging of volume datasets such as these provides a very effective means of communicating findings to the clinician for surgical or therapy planning. The volumetric rendering technique is a new method of creating 3D images of medical volume datasets. It produces images with unprecedented fidelity and accuracy. This paper illustrates the volumetric rendering technique and its application to clinical medicine.

Introduction
The newer imaging modalities such as Computed Tomography and Magnetic Resonance Imaging have resulted in a large increase in the amount of information available to the Radiologist, with subsequent improvement in diagnostic performance. Diagnosis, however, is only part of the solution in patient care; it is followed by treatment. The treatment of the patient after diagnosis is a critical part of the care process. The radiologist is called on to communicate the findings to the physician who is responsible for treatment of the patient. 3D imaging is a very effective method of communicating information about radiologic studies to the referring clinician.

There are a number of different techniques which have been developed to create three dimensional images; these include thresholding techniques (Octree, Fitted Surfaces, Marching Cubes, etc) and percentage based techniques (Volumetric Rendering). Technically, these methods have evolved as the speed of the computing hardware increased. Initial attempts at three dimensional imaging produced noisy, unclear images with little clinical value. These methods have now reached a level of sophistication such that they provide a useful clinical tool to the radiologist and the clinician.

Early attempts dealt primarily with imaging bone from C.T. data. All of the early techniques used an algorithm called thresholding to isolate the bone volume elements (voxels) in the scanned volume. This technique results in images that have a high noise content and little of the detail that was found in the original data set. This poor image quality has caused much skepticism to arise concerning the efficacy of 3D imaging. Because communication to the clinician is the primary focus of 3D imaging, images with noise and artifact limited the utility.

Volumetric rendering does not suffer from the problems plaguing thresholding based imaging. Volumetric rendering uses percentage classification to assign mixtures of fat, soft tissue, and bone to each voxel. The assignment of mixtures to partial volumes is critical in avoiding artifacts and noise. A disadvantage of the volumetric rendering technique is the requirement for high speed computer hardware; fortunately, a number of high speed platforms that can support volumetric rendering now exist. The first part of this paper will focus on the technical aspects of these types of three dimensional imaging techniques.

At our institution, we have been using three dimensional imaging in a clinical setting for over three years. We have applied the technique to all the major joints (hip, shoulder, ankle, knee, and elbow), and to the oncologic patient. New research indicates a use for three dimensional imaging in the lung. We find that three dimensional imaging is not a substitute for planar imaging, but provides an adjunct to planar imaging. Planar imaging although very useful for diagnosis does not fully address the problem of treatment planning. The combination of planar imaging and three dimensional imaging is ideal. Three dimensional imaging is not a diagnostic tool; it is a therapeutic tool, designed to help manage the patients treatment after the diagnosis is made. The second part of this paper will focus on the clinical application of the volumetric rendering technique.

Volumetric Rendering
The computer graphics division of Lucas Films (San Rafael, CA) now known as PIXAR (San Rafael, CA)
developed an algorithm termed Volumetric Rendering. Volumetric Rendering is a technique which allows the generation of 3D images of any volume data set. Several features of this technique alleviate problems found in using other image generation techniques. Volumetric Rendering allows for the use of a mixture paradigm for representation of the volume to be rendered. Volumetric Rendering uses mathematical techniques which reduce or eliminate aliasing (a significant source of computer generated artifacts).

The Volumetric Rendering of C.T. data can be broken into four steps: Volume formation, classification, rotation, and projection. A surface detection and shading step can be included to produce shaded images. We refer to images in which the surface detection and shading steps are omitted as "unshaded images" and images in which they are included as "shaded images." We find that bony conditions are well displayed using the unshaded images, whereas conditions involving soft tissue require the shaded technique. We will describe the unshaded technique of imaging. The unshaded process illustrates well the principles behind volumetric rendering. The shaded technique is simply an extension of the unshaded process that produces images in which an artificial light source is used to shade the anatomy.

The unshaded imaging process begins with formation of the volume of data. This consists of stacking a contiguous set of slices one on top of each other so as to form a volume of data. Each pixel in a particular slice now becomes a voxel (volume element) in the volume. At this time bi-cubic interpolation is performed to produce cubic voxels. This interpolation is performed so that the new slices generated have an inter-slice spacing equal to the pixel size. Thus, after volume formation, there exists a volume of data which contains voxels that are perfect cubes and represent an interpolated Hounsfield density.

The next step in the process is classification. Classification assigns to each voxel percentages of different materials that are present in the voxel. There are four major tissue types that can be readily separated by CT attenuation: air, fat, soft tissue, and bone. In general each voxel represents a mixture of these four materials. In the human body, it is rare to find voxels that are a mixture of more than two materials. The common mixtures are air/fat, fat/soft tissue, and soft tissue/bone.

The classification technique estimates the amount of each type of tissue present in a volume element. This estimation is done by using a set of trapezoidal classification curves. These curves attempt to model the measured CT numbers for each tissue and the volume averaged tissue mixtures. A voxel that reads +1000 Hounsfield units will be classified to 100% bone. A voxel that reads +50 Hounsfield units will classified to 100% soft tissue. A voxel reading in between these numbers, for example +100 Hounsfield units will be classified to perhaps 60% soft tissue and 40% bone. Thus, this intermediate value voxel represents a volume average of soft tissue and bone. This classification process is applied to each voxel in the volume. The result of the classification is a volume in which each voxel has been assigned percentages of each of the tissue types.

At the time that classification into tissue types is done, opacity is assigned to each volume element. Each of the tissue types (fat, soft tissue, and bone) are assigned an opacity value chosen in regard to which type of tissue is to be imaged. If bone is to be viewed, bone is given a high opacity value, and soft tissue is given a low opacity. If soft-tissue is to be viewed, the reverse is chosen. A volume elements opacity is then determined by the amount of each material classified into the voxel and the assigned opacity of those tissues. A voxel containing 40% soft tissue and 60% bone will be given an opacity equivalent to 40% of the assigned opacity of soft tissue plus 60% of the opacity assigned to bone.

The next step in the unshaded image generation process is transformation of the classified volume to the viewing orientation. For clinical use we perform rotation about one selected axis. This axis can be any of the x, y, or z axes. (Conventionally, the z axis is considered to be perpendicular to the scanning plane and assumed to be parallel to the spine. The x axis is defined by the intersection of the transaxial and coronal plane, and the y axis is defined by the intersection of the transaxial and the sagittal plane.) In clinical practice rotation about the z axis (termed spinal rotation) and x axis (termed somersault rotation) are the only ones of use. Rotation about one axis is performed by using a two dimensional anti-aliased rotation. Because the rotation is about one of the coordinate axes, by rotating two dimensional planes perpendicular to this axis, we perform the desired rotation of the entire volume. When rotating about the spinal axis, transaxial slices are rotated. When rotating about the somersaulting axis, sagittal slices are rotated. The final transformed, classified volume is now ready for projection to form a two dimensional image.

Following rotation, the projection is performed by computing a weighted sum of voxels in columns
parallel to the viewing direction. Each column thus produces one pixel in the final image. The weighted sum is known as a merge over operation used in compositing images. The sum is weighted by the opacity of each voxel in the column. Voxels with a high opacity contribute more to the sum, while voxels with low opacity contribute little. The sum is computed from back to front (in relation to the viewing orientation) so that voxels near the back are obscured by opaque voxels near the front of the volume. By computing this sum for each column in the volume, a two dimensional image is formed. This projection can be done on a slice by slice basis (using slices oriented perpendicular to the viewing plane). When projecting a volume rotated about the spinal axis the summation is performed for columns of voxels that have constant x and \( y \) coordinates—the \( z \) coordinate is varied. Thus each pixel in the resultant two dimensional image corresponds to a column defined by the \( x \) and \( z \) coordinates.

Generally we compute a number of images with viewing orientations placed at intervals simulating 360° rotation of the volume. These images are displayed rapidly and sequentially in an animated video loop. We find that the simulated motion effect produces valuable depth cues for the human eye. This effect is particularly noticeable with the unshaded images. When unshaded images are viewed statically, the depth information is much less apparent. We commonly use video tape to archive the studies because of the importance of motion.

The images generated using this unshaded rendering process have an appearance which is reminiscent of a conventional radiographic image (see figure 1). These images are particularly useful for examining bony abnormalities. The bones are semi-transparent and therefore internal detail is visible as well as surface detail. Unfortunately, the unshaded technique does not work well for imaging soft tissue. The high variability of bone density causes the unshaded algorithm to produce the perceived detail. Soft tissue attenuation values are confined to a far narrower spectrum, making it more difficult to separate, for example, a vessel or node from adjacent muscle. The shaded surface method, on the other hand, allows reliable separation of adjacent soft tissue structures down to 2-3 mm. To expedite imaging of soft tissue we use a shaded surface method of volumetric rendering. The shaded surface algorithm is very similar to the shaded method, with the exception that a surface detection and shading step is included. Figure one shows many examples of volumetric rendering of volume medical data.

**Clinical Applications**

In determining which clinical applications 3D imaging would be useful one can apply several simple criteria and concepts:

1. The more complex the anatomy to be evaluated the more likely 3D visualization is likely to be needed.
2. The more extensive the pathology (i.e., complex fracture, congenital malformation, tumor extension), the greater the need for 3D visualization.
3. The more variety in therapeutic options available to the clinician, the more important additional information is in arriving at the correct procedural choice.
4. The more difficult the clinical decision, the more likely the 3D information will be needed.

These rules are based on our belief that the major role for 3D imaging is in clinical management decisions rather than in diagnosis. This is not to say that a 3D display will not allow one to make the correct diagnosis, but rather is a conceptual notion where 3D should fit in the diagnostic scheme. The radiologist and/or clinician should carefully review the transaxial CT images supplemented by the two-dimensional reformations into coronal, sagittal and/or oblique planes. In cases of trauma the presence or absence of a fracture and/or dislocation should easily be made from the planar images. The 3D display is then reviewed to obtain a better understanding of the fracture and its true orientation. This information is particularly useful in the event surgical repair is attempted. However, it would be counter-productive to only review the 3D images and disregard the original planar data.

With this in mind the major clinical applications of 3D imaging have been for trauma, congenital deformities, oncology and degenerative arthritis. The major anatomic areas evaluated have included the acetabulum and pelvis, shoulder, spine, knee, and ankle.

**Scanning Technique**

As with any type of 3D imaging technique, the data acquisition techniques are critically important in obtaining satisfactory images. The wide variety of available CT scanners with varying scan parameters (i.e., mAs, collimation, reconstruction algorithm) makes it impossible to define a standard set of scanning protocols for the examination. However,
several basic principles need to be followed in order to optimize the 3D examination.

1. The patient must be made as comfortable as possible prior to the exam to help prevent inadvertent motion during the study. We have found it invaluable to tape the patient when possible to prevent inadvertent motion. For example, on a pelvic CT we gently tape the patient's hips, knees and ankles together; this tends to reinforce the importance of lying still. A few words of encouragement both prior and during the scan from the technologist will also help keep the patient's mind on the task at hand.

2. Scans should be closely spaced with an overlap, to help preserve final image quality. The standard cranial study is often done with 1.5 mm slice thickness at 1.5 mm intervals or 3 mm thick sections at 3 mm intervals. This often results in a stack of 100 or more slices. Most of the other clinical 3D applications are done with a stack of between 20 and 60 CT slices. Our standard protocol is 4 mm collimation at 3 mm intervals; a 1 mm overlap10,11,12

3. Scans done for a 3D exam need not be with high mAs. This compromise helps maintain a relatively low dose for the examination. Our standard pelvic 3D/CT in the adult involves less radiation than a full series of pelvic films. On a Siemens Somatom DR, the standard scan parameters are either 3 sec, 230 mAs, 125 kVp or 4 sec, 310 mAs and 125 kVp. We are now routinely scanning pediatric patients at 3 sec, 140 mAs and 125 kVp.

When these general guidelines are used, it is possible to obtain a good 3D study with almost every patient.

Pelvic and Acetabular Fractures

One of the most useful applications of three-dimensional imaging has been in the evaluation of the traumatized pelvis13,14. It has previously been shown that even in the best of circumstances, up to 70% of pelvic plain films may be suboptimal due to a number of factors including superimposed air, feces and foreign matter or suboptimal patient positioning or exposure15. The areas of the pelvis most often obscured include the posterior pelvic ring, sacrum and SI joints and the acetabulum itself. Initial use of CT in the late 70's and early 80's found that with standard transaxial images alone there was an increased detection of fractures as well as definition of the fracture extent and localization of intra-articular fragments. The introduction of two-dimensional and three-dimensional imaging is an attempt to expand the information gained from the transaxial CT's into a more useful model that the surgeon can study when making patient management decisions and in the actual surgical procedure. Although the actual information as to the extent of fracture is present on the transaxial images it is difficult to create a mental visualization of the more complex injuries. This is true for the radiologist, but is especially true for the non-radiologist who is less trained in cross-section image interpretation. The referring physician (which in this case is the orthopedic surgeon) must be presented a set of information that can be used by him for the care of the patient.

In general, to evaluate the pelvis a standard set of images is generated (see figure 2). We produce images of the bony anatomy rotating about the spine (spinal axis rotation) and the pelvis (somersaulting rotation). The somersaulting rotation is invaluable in determining the overall integrity of the pelvic ring. Displacement of the medial wall of the acetabulum can also be readily determined using this rotation. This view is generally unattainable by any other means. When only one side of the pelvis is affected, we will mask off the contra-lateral pelvis (render it transparent) in order to view the involved half with no obstruction. This standard set of views addresses many of the problems in pelvic trauma.

The Shoulder Joint

Conventional radiography of the shoulder is limited due to overlapping structures and inability to obtain true lateral views16,17. Although many of the special views have been developed, they are often impossible to obtain in the traumatized patient. In addition, fractures in this region are very subtle and can be easily missed. This is particularly true of fractures of the glenoid and scapular body.

The use of three-dimensional imaging allows the easy visualization of the entire shoulder joint including the acromioclavicular joint and sternoclavicular joint18 (see figure 3). The two-dimensional images are particularly helpful in these cases in measuring degree and angle of displacement, although the three-dimensional images truly do best define the full extent of injury. The ability to edit images allows for visualization of only the scapula which is particularly helpful in detecting the subtle body of scapula fractures. In addition, the humerus can be removed from the joint allowing direct visualization of the glenoid. The glenoid is often associated with injury which, if missed, can lead to future shoulder dislocations. We find that producing unshaded translucent images of the shoulder and scapula can be invaluable in detecting and defining subtle fractures.
These structures fully test the ability of the three dimensional rendering technique at producing accurate images of thin bones and subtle, non-displaced fractures.

**Spine and Sacrum**

The presence of fractures of the spine are related to the mechanism of injury. The majority of patients with spinal trauma in our institution are automobile accidents or falls. Sacral fractures are commonly associated with pelvic acetabular fractures. Involvement of the sacroiliac joint is not uncommon, particularly in ring-type fractures. 2D and 3D imaging provide the ability to look at the entire pelvis in a single view and ascertain the extent of injury in complex multidimensional fractures (see figure 4). Using multi-planar reconstruction and choosing planes cutting along the curvature of the sacrum, one can bring into view the sacral foramina. Looking at the sacral foramina in face allows one to ascertain the full extent of the injury, particularly in vertical shear fractures which often do involve the foramen. The two-dimensional views are also very good at looking small fragments avulsed off the iliac or sacral side of the SI joint during injury. The three-dimensional images provide the best understanding of the full extent of sacral fracture. Both the somersaulting and spinal rotations help provide an understanding of the complicated injuries. The spinal rotation provides for easy evaluation of the amount of displacement of the sacrum.

The goal of 3D imaging in lumbar or cervical spine fractures is for a better visualization of the extent of injury and definition of adjacent structural involvement. In the lower lumbar spine, detection of a fracture and displacement can all be clearly defined on the 3D reconstruction. The value of the 3D images in these cases is to mainly to look at areas such as the posterior elements to determine if there is any compression present; this is optimally viewed on these images. The extent of injury of the spinal injury cord can also be addressed at the same time. The type of three dimensional reconstruction technique used in the spine can be very important, since the use of sub-optimal images in evaluating certain disease types would not be good practice. In general we find that volumetric rendering (especially the unshaded views) give an unbiased representation of the actual anatomy and pathology.

**CONCLUSION**

The volumetric rendering technique is a superior method for producing accurate three dimensional images of volume imaging data. The method does not introduce computer generated artifacts (fake bone, or false holes in bone), nor does it produce distracting aliasing (jaggies). The clinical application of this technique should be guided by the premise that three dimensional imaging is not necessarily a diagnostic tool, but a therapeutic tool. Generally, diagnosis can and should be done using the conventional planar images or multiplanar reconstructions. Three dimensional images should be used to help communicate with the referring physician, as well as help him/her with surgical or therapy planning. Three dimensional imaging is most useful in cases where complex anatomy or disease is present. These applications presently include the pelvis, shoulder, knee, ankle, and spine. Current research efforts are now aimed at producing images of the internal organs, the brain, and the lungs. As this new research begins to produce results, the use of three dimensional imaging will expand to a very wide range of clinical applications. The ability to optimally present the acquired image data to the referring physician is of prime importance to the radiologist is the attempt to better serve the health care community.

**References**


Figures

Figure 1
Unshaded image of the skull.

Figure 2a
Figure 2b
Right Acetabular Fracture.

Figure 3a
Figure 3b
Right Humerus Fracture

Figure 4
Sacral strut fracture.