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REVIEW ARTICLE

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# Skeletal 3-D CT: advantages of volume rendering over surface rendering

**Abstract** Both surface rendering and volume rendering have been extensively applied to CT data for 3-D visualization of skeletal pathology. This review illustrates potential limitations of each technique by directly comparing 3-D images of bone pathology created using volume rendering and surface rendering. Surface renderings show gross 3-D relationships most effectively, but suffer from more stairstep artifacts and fail to effectively display lesions hidden behind overlying bone or located beneath the bone cortex. Volume-rendering algorithms effectively show subcortical lesions, minimally displaced fractures, and hidden areas of interest with few artifacts. Volume algorithms show 3-D relationships with varying degrees of success depending on the degree of surface shading and opacity. While surface rendering creates more three-dimensionally realistic images of the bone surface, it may be of limited clinical utility due to numerous artifacts and the inability to show subcortical pathology. Volume rendering is a flexible 3-D technique that effectively displays a variety of skeletal pathology with few artifacts.

**Key words** Three dimensional imaging · Computed tomography (CT) · Image Processing

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## Introduction

Skeletal applications of 3-D medical imaging were among the first to be developed [1] and remain the most common clinical application of 3-D imaging. Three-dimensional CT has been shown to have an impact on diagnosis and surgical management in a number of skeletal applications including craniosynostosis [2], ankle fractures [3], acetabular fractures [4], and shoulder trauma [5]. With the emergence of spiral CT [6, 7], recent advances in computer graphics hardware, and the general interest in minimally invasive therapies, there has been a renewed interest in 3-D medical imaging. Because spiral CT allows the acquisition of an entire volume over a short time, the resulting multiplanar and 3-D images have few motion artifacts [8, 9]. Despite the emergence of MRI as an important musculoskeletal imaging modality, CT remains an important clinical tool in the evaluation of a number of musculoskeletal problems including trauma, inflammatory disease, and tumors.

Three-dimensional rendering is the process of creating a realistic 2-D image that intuitively conveys 3-D relationships [10]. Three-dimensional images present the findings of a study in a way that can be easily understood by nonradiologists. They can often be helpful to the radiologist as well, particularly in cases of complex anatomy or pathology. The rendering technique used to create a 3-D medical image greatly affects the form, quality, and usefulness of the final 3-D image. Surface rendering and volume rendering are the two principal rendering techniques applied to bone imaging. It is important that the clinician understand the basic algorithms of each rendering technique and the images that result from them, in order to critically evaluate the literature and factor the limitations of each technique into clinical decisions.

Surface rendering is widely available in commercial CT image processing packages. Volume rendering is a newer and more computer-intensive technique [11–13] that is just now becoming incorporated into commercial-

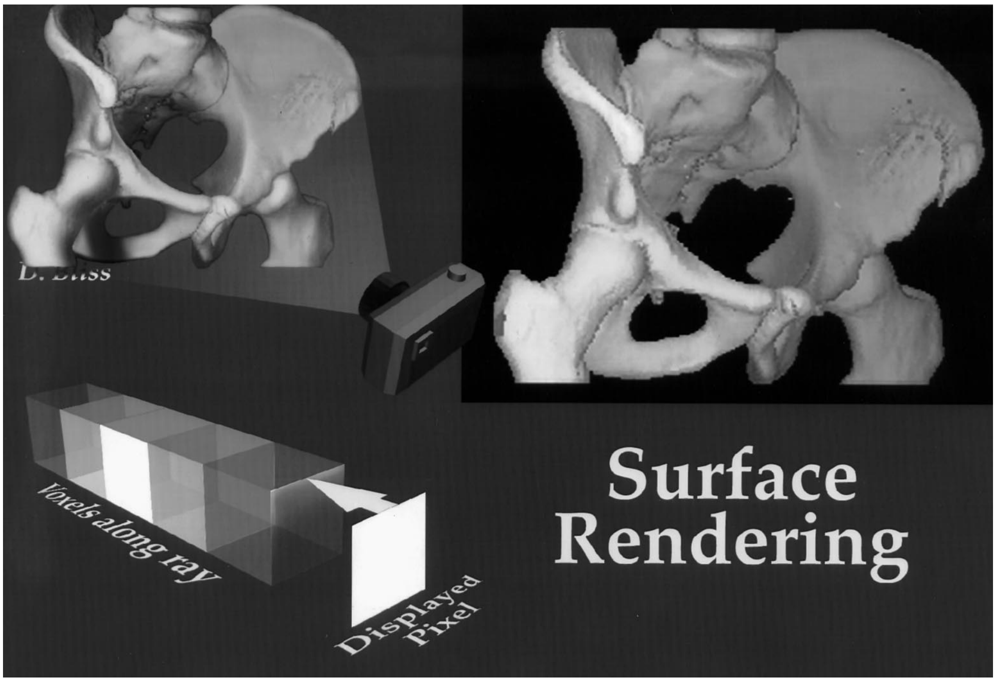



**Fig. 1** The surface-rendering algorithm as applied to the pelvis. The first voxel encountered along the projection ray which is above the user-defined threshold is selected as the bone surface. The resulting pixel value contains no information from beyond that voxel. The displayed pixel intensity is calculated from the mathematical interaction of a lighting model and a surface model

ly available software. Since 1986, we have had extensive clinical experience with 3-D imaging at our institution using both volume rendering and surface rendering [3–5, 8–10, 12, 13]. In order to illustrate the strengths and weaknesses of each technique, we selected four CT datasets of skeletal pathology which present specific difficulties to 3-D rendering algorithms, consisting of two cases of subcortical pathology and two cases in which the region of interest is hidden by overlying bone.

## Data acquisition techniques

Datasets were acquired using a Siemens Somatom Plus or Plus-S scanner (Siemens Medical Systems, Iselin, NJ) with the spiral CT option. The sets in cases 1 and 4 were acquired using helical CT with a scan duration of 24 or 36 s. The table incrementation speed was 4 mm/s, with 4 mm collimation, 210 mAs, and 120 kVp. Reconstructions were performed every 3 mm using 180° interpolation. Datasets in cases 2 and 3 were acquired using dynamic CT with contiguous 4-mm slices. The axial slices were reduced from a 512×512 pixel matrix to 256×256 and transferred to a SPARCserver 20 (Sun Microsystems, Mountain View, CA) or Crimson with Reality Engine (Silicon Graphics, Mountain View, CA) image processing workstation. Studies were edited using the IPDoc software (Advanced Medical Imaging Lab, Johns Hopkins Hospital) to exclude casts. In the acetabular fracture case (case 3), manual editing was used to bisect the pelvis and disarticulate the right hip joint. No other manual editing was performed. Interactive video loop displays consisting of 16 images rotating around the *x* (tumbling) and *z* (spinal rotation) axes were created using both surface and volume rendering.

Surface renderings were created using the Siemens Magic View software (Siemens Medical Systems, Iselin, NJ). Thresholds of 150–220 HU were subjectively applied to select bone and exclude other structures. Surface-rendering algorithms classify each voxel within a volume as belonging to or not belonging to the object being rendered, usually by comparing each voxel to one or more user-selected threshold values which define the range of pixel intensity values that represent the material of interest. Identifying all pixels belonging to an object effectively describes the object’s surface, which the computer typically models as a collection of polygons and displays with surface shading (Fig. 1) [14].

Volume renderings were created with the IPDoc software (Advanced Medical Imaging Lab, Johns Hopkins Hospital) using a 3-D bone imaging application developed by our research group. Three specific volume-rendering algorithms were used: unshaded bone, shaded bone, and shaded opaque bone. A percentage classifier algorithm is used to classify each voxel into material percentages of bone based on the relationship of the individual pixel intensity to the pixel intensity histogram typical of bone. Percentage classification assumes that voxels containing a given tissue form a gaussian distribution of intensities around a central value that theoretically represents a voxel composed 100% of that tissue type. Above and below the ideal value are ranges of intensities where the probability of a voxel containing the tissue of interest is between 0 and 100%. The software approximates the gaussian distribution as a trapezoid (Fig. 2). The percentage of each voxel which is composed of bone is assumed to be proportional to the probability that a voxel of the given intensity contains bone.

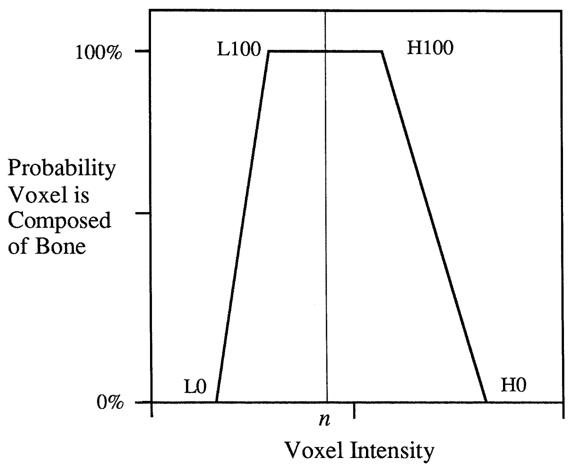



**Fig. 2** Illustration of the percentage classification technique for classifying voxel composition. The nominal value of a voxel composed of 100% bone is represented as *n*. The volume-rendering algorithm assumes that the amount of bone contained in a voxel is proportional to the probability that the voxel contains bone. Note that simple thresholding is the case where segments L0–L100 and H0–H100 are vertical. In that case any voxel with a CT number between L0 and H0 is assumed to contain 100% bone, while those outside these values is assumed to contain 0% bone

A weighted sum is computed from the estimated bone composition of all voxels along a line extending from the viewer through the data volume. This sum is repeated for each pixel in the displayed image (Fig. 3). The shaded bone and shaded opaque bone algorithms estimate the location of material surfaces based on the local gradient of the voxel composition and use these estimates to enhance edges and regions of inhomogeneity [15]. The lighting model used to provide surface shading consists of a point source of white light located at an infinite distance above and to the left of the observer. Shadows and reflections are not depicted. The opaque bone algorithm differs from the shaded bone only in that a higher "opacity" is assigned to bone, and so distant structures are obscured by nearer structures.

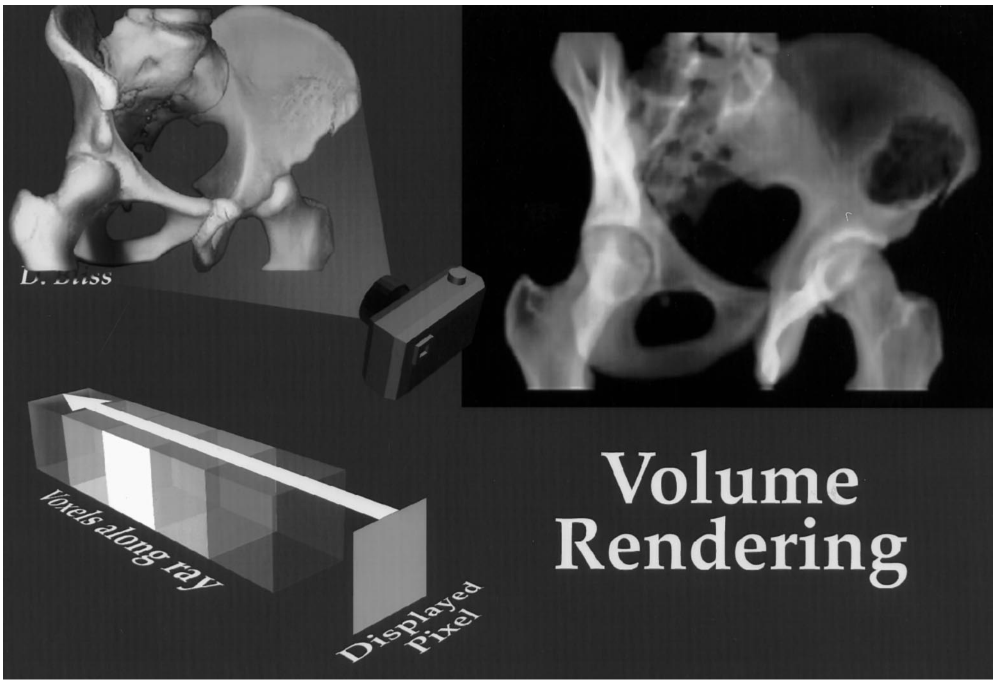
## Comparison of techniques

### Surface rendering

Surface rendering has several important advantages. Because they reduce the original data volume down to a compact surface model, surface-rendering algorithms can operate very rapidly on modern workstations. The realistic lighting models used in many surface-rendering algorithms can provide the most three-dimensionally intuitive skeletal images. Finally, the distinct surfaces in surface reconstructions facilitate clinical measurements.

Two serious drawbacks are associated with the use of surface rendering for the display of skeletal pathology.

**Fig. 3** The volume-rendering algorithm as applied to the pelvis. The values of all of the voxels along a line extending from the observer through the object of interest contribute to the resulting pixel value, allowing the visualization of subcortical and hidden lesions. The volume-rendered image shown was created using the unshaded bone algorithm



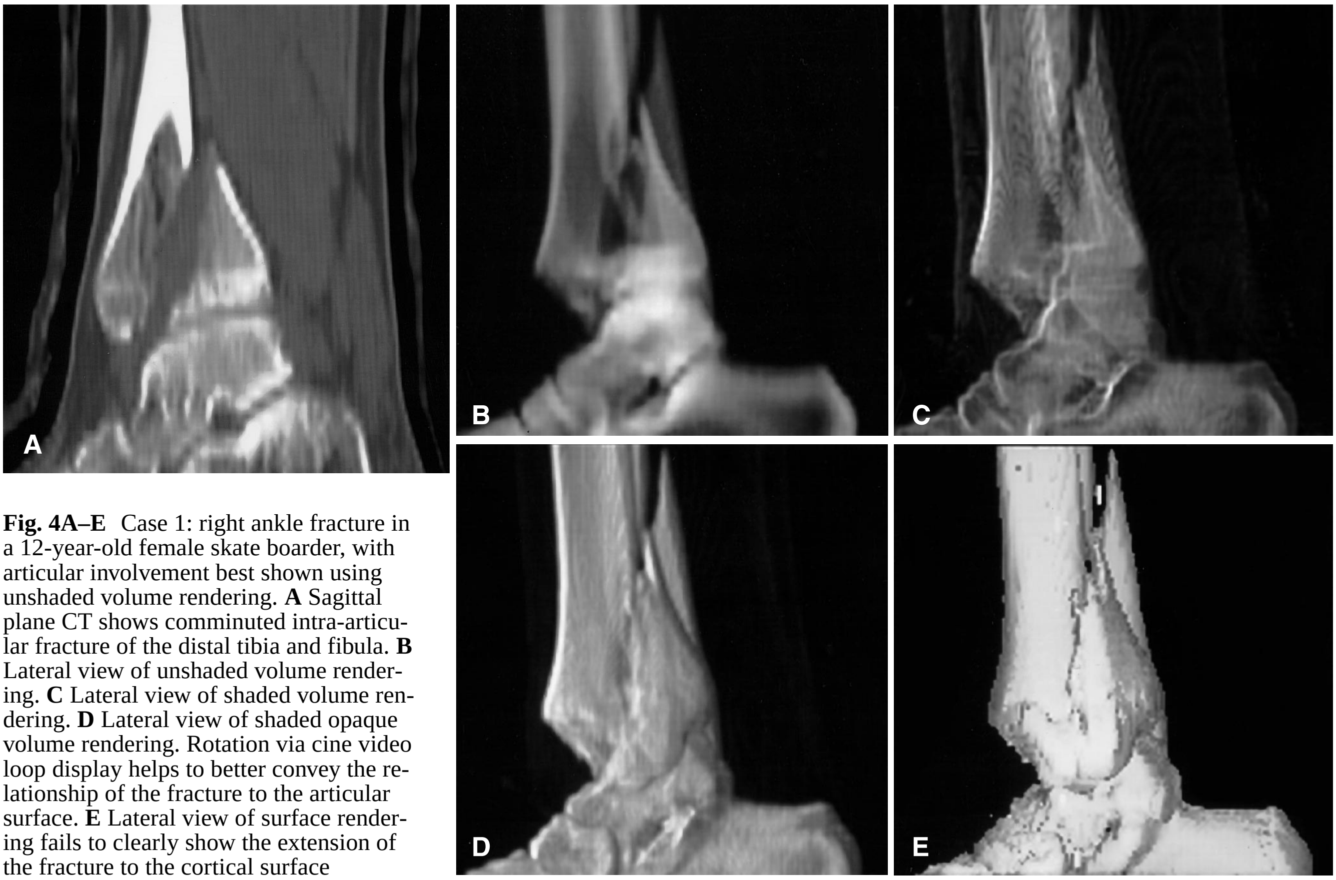



**Fig. 4A–E** Case 1: right ankle fracture in a 12-year-old female skate boarder, with articular involvement best shown using unshaded volume rendering. **A** Sagittal plane CT shows comminuted intra-articular fracture of the distal tibia and fibula. **B** Lateral view of unshaded volume rendering. **C** Lateral view of shaded volume rendering. **D** Lateral view of shaded opaque volume rendering. Rotation via cine video loop display helps to better convey the relationship of the fracture to the articular surface. **E** Lateral view of surface rendering fails to clearly show the extension of the fracture to the cortical surface

Most fundamentally, surface renderings depict only the bone surface. Most of the available data is not incorporated into the 3-D image. In cases where the pathology of interest is subcortical or obscured by overlying bone (Figs. 4–7), surface rendering does not display the most important information in the dataset. The second serious drawback is poor image fidelity. Surface renderings simplify the data into a binary form, classifying each pixel as either 100% bone or 0% bone. The finite voxel size in medical data produces many voxels that are only fractionally composed of bone, and classifying them as all or none introduces stairstep artifacts into the image [10]. By varying the threshold minimally, fracture gaps can appear to open and close, bony processes lengthen and shorten, and “holes” in the cortex are created and fused [13]. These artifacts, coupled with the inability to show subcortical detail, can make it impossible to visualize important aspects of skeletal pathology.

## Volume rendering

Volume rendering has two principal advantages over surface rendering. First, percentage classification provides a physically realistic depiction of volume-averaged CT data [10, 11]. Because the voxels are of finite size, many voxels contain multiple tissue types and are only fractionally composed of bone. Volume rendering with percentage classification accurately depicts this physical reality. Second, volume rendering incorporates all of the data contained in the volume into the displayed image. Volume renderings can show multiple overlying and internal features, and the displayed intensity is related to the amount of bone encountered along a line extending through the volume. Surface shading [15] and increased opacity can be used to enhance 3-D understanding of the volume rendered images. The main drawbacks associated with volume rendering are the increased computational cost (less of an issue with modern workstations) and the difficulty in appreciating 3-D relationships in very transparent volume-rendered images.

### *Unshaded bone*

The unshaded bone algorithm creates images that appear similar to plain radiographs. Any manipulation of the data (including surface shading) is a potential source of arti-

**Fig. 5A–E** Case 2: Paget's disease in a 66-year-old man, well shown using volume rendering but obscured by surface rendering. **A** Axial CT shows cortical thickening, bony expansion, and sclerosis of the right hemipelvis. **B** Unshaded volume rendering shows sclerosis and cortical thickening in a manner similar to a plain radiograph. **C** Shaded volume rendering shows enhancement of the cortical surface, areas of sclerosis, and the corticomedullary junction. Shading makes the differences between the two sides more difficult to appreciate. **D** Shaded opaque volume rendering shows similar enhancement of areas of changing intensity. Increased opacity aids 3-D understanding. **E** Surface rendering gives an essentially normal appearance – no subcortical pathology is visible



fact. While the unshaded bone algorithm created the least three-dimensional images in this study, the lack of surface shading and enhancement makes these images the simplest, most artifact-free of the three volume rendering techniques. Video loop rotation greatly enhances 3-D understanding when viewing these images. In our experience, the ability to depict multiple overlying structures with few artifacts has made the unshaded bone algorithm the most useful technique for most skeletal applications.

*Shaded bone*

The shaded bone algorithm incorporates surface shading and enhancement at interfaces of materials with different CT numbers. This can be useful for accentuating lytic or sclerotic lesions, or clearly defining the medullary canal. However, surface enhancement increases computer rendering time and can serve as a source of artifact which can make these image difficult to interpret. In practice,

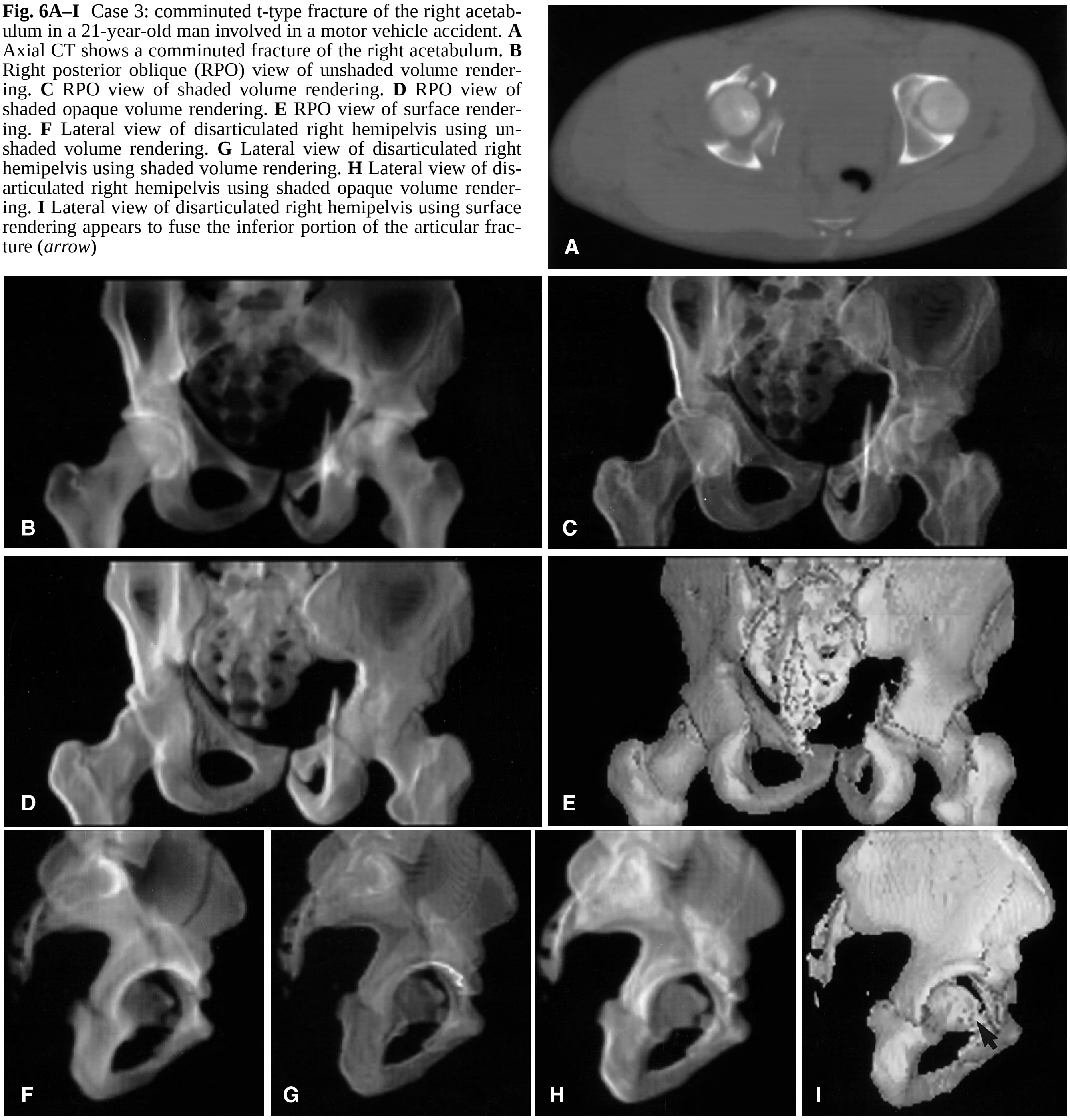


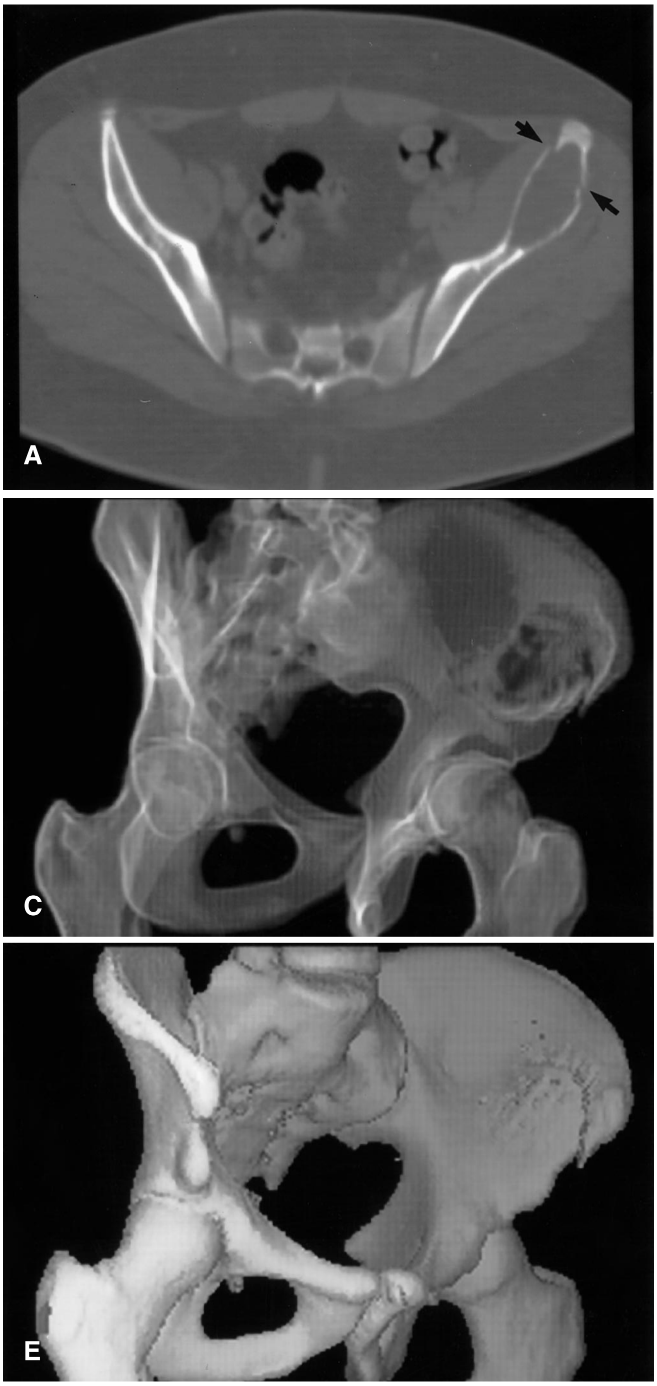

**Fig. 6A–I** Case 3: comminuted t-type fracture of the right acetabulum in a 21-year-old man involved in a motor vehicle accident. **A** Axial CT shows a comminuted fracture of the right acetabulum. **B** Right posterior oblique (RPO) view of unshaded volume rendering. **C** RPO view of shaded volume rendering. **D** RPO view of shaded opaque volume rendering. **E** RPO view of surface rendering. **F** Lateral view of disarticulated right hemipelvis using unshaded volume rendering. **G** Lateral view of disarticulated right hemipelvis using shaded volume rendering. **H** Lateral view of disarticulated right hemipelvis using shaded opaque volume rendering. **I** Lateral view of disarticulated right hemipelvis using surface rendering appears to fuse the inferior portion of the articular fracture (*arrow*)

we have found the shaded bone to be the least helpful of the three volume-rendering algorithms presented.

*Shaded opaque bone*

The opaque bone algorithm is very useful in applications in which surface detail and 3-D relationships are of primary importance. The decreased transparency in these images can make it more difficult to appreciate multiple overlying structures. However, opacity dramatically improves 3-D understanding, and the opaque shaded images were the only volume renderings in this study that intuitively portrayed important 3-D anatomical relationships with a degree of clarity similar to that of the surface renderings. In the extreme case where the opacity is 100%, no internal detail is visible and the resulting image is effectively a surface model. We do not routinely

**Fig. 7A–E** Case 4: aneurysmal bone cyst in a 15-year-old boy, well shown using volume rendering but obscured by surface rendering. **A** Axial CT shows lytic lesion of the left iliac bone with pathologic fracture (*arrows*). **B** Right anterior oblique (RAO) view of unshaded volume rendering. **C** RAO view of shaded volume rendering. **D** RAO view of shaded opaque volume rendering. All three volume algorithms show the extent of the bone cyst and the associated pathologic fracture. **E** RAO view of surface rendering best demonstrates cortical bulging and the course of the pathologic fracture but fails to display the underlying cystic lesion




use 100% opacity because it prohibits the visualization of subcortical detail.

## Future directions

The flexibility of the volume-rendering technique is an important advantage over surface rendering. The user can tailor the bone opacity and presence or absence of surface shading to the clinical problem. Ideally, the user would be able to interactively change these parameters in real time, thereby maximizing both 3-D perception and subcortical visualization in a single image. Real-time (subsecond) volume rendering has recently become possible by taking advantage of parallel computer architectures in new graphics workstations [16]. While initial real-time volume rendering applications have not yet incorporated surface shading, they do allow real-time changes in opacity. This type of interactive approach to 3-D visualization promises to be more available and practical in the near future with reasonably priced graphics workstations. Routine clinical use of this kind of technology will permit a change in the way that radiologists work, from viewing standard views at a light box to interactive exploration of the data with a variety of computer-based image processing techniques.

## Conclusions

Different vendors offer different versions of the two rendering techniques discussed in this paper, and their quality may vary. Despite these variations, the fundamentally different ways in which volume rendering and surface rendering algorithms process and display medical data have important implications. While surface-rendered images of skeletal pathology often appear more three-dimensional than those created using volume rendering, their clinical utility can be limited by poor image fidelity and the inability to show subcortical detail. Variations of the volume-rendering algorithm demonstrate both surface and internal detail and allow the clinician to tailor the use of surface shading and opacity to clearly demonstrate most skeletal pathology. Flexibility and superior image fidelity make volume rendering a useful technique for a variety of skeletal 3-D CT applications.

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