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CLINICAL APPLICATION OF THREE DIMENSIONAL COMPUTED TOMOGRAPHY IN DIAGNOSTIC RADIOLOGY

Pei-Jan Paul LIN[1] and Andrew K. POZNANSKI[1,2]

Department of Radiology, Northwestern University, Medical School, Chicago, Illinois 60611, U.S.A.

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Abstract. Most three-dimensional (3-D) images have been reconstructed from CT images in medicine, and are processed through surface rendering techniques. In this paper, the basic principles of surface rendering techniques are discussed in conjunction with the volumetric rendering with the original image sequence obtained from the CT scanners. The discussions, however, are not designed for programmers or computer buffs. Although 3-D image display has limited diagnostic values, it has been shown useful in aiding various surgical procedures and treatment planning of radiation therapy patients via tumor volume measurements. In this article, clinical examples (some based on the actual clinical cases and some are for demonstration purposes) are included to show the usefulness and the application of 3D imaging.

I. INTRODUCTION

Digital technology, in general, has continuously impacted on the overall quality of human life in the past decades. Perhaps, the single most affected area in medicine, is diagnostic radiology. Most diagnostic imaging procedures are two-dimensional; i.e., in routine radiography [and fluoroscopy], the image obtained is a superimposed picture of a three-dimensional object [patient]. In tomographic imaging such as conventional tomography, computed tomography (CT), magnetic resonance imaging (MRI), etc., the image being viewed by radiologist is a slice or a thin section of the three-dimensional volume. Although, true 3-D radiography has been used in the past by obtaining 2 angled views of radiographs for stereoscopic viewing.

[1]Department of Radiology, Northwestern University, Medical School, 303 East Chicago, Avenue, Chicago, Illinois 60611, U.S.A.
[2]Department of Radiology, Children's Memorial Hospital, Lincoln & Fullerton Avenues, Chicago, Illinois 60614, U.S.A.

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The three dimensional nature and the geometrical spatial relationship of various anatomical parts must be reconstructed in the mind of radiologist. Even with the trained eyes of radiologist, reconstruction of the three-dimensional image from a given set of two-dimensional images is not a simple task.

The advent of 3-D imaging reconstructed from the CT images has proven very helpful in the interpretation of complex anatomical structures such as skull and pelvis (Udupa: 1983). 3-D imaging does not replace the detailed diagnostic information provided by the CT images. It supplements and assists in the visualization of the morphologic information so that a more accurate diagnosis can be offered. 3-D imaging has also been particularly useful in planning surgical procedures.

II. METHODS OF 3-D IMAGE GENERATION

Although it is technically feasible to employ other types of imaging modalities, almost all three-dimensional medical imaging work has been performed with CT images. Some MR images have also been used with varying degree of success and expected to occupy equally important role as that of 3-D CT images. While 3-D display of 3-D objects is possible with holography (Fujioka, *et al.*: 1988), 3-D images are generally displayed using a two-dimensional screen. Using various methods and techniques such as "reflective surface shading", "movement parallax", "perspective deformation", etc., objects are displayed on the two dimensional screens with optical illusion of three dimensional perception.

Hence, it is appropriate to focus the discussion of the 3-D image display and 3-D image generation based on the rendering of 3-D objects utilizing CT images. The process can be explained as following:

(1) *CT image acquisition.* Before the 3-D images can be synthesized, the original 2-D CT images must be acquired. Acquisition of such images is typically conducted with CT slice width of 1.5 mm [to a maximum of 3.0 mm] and matrix size of 512×512. The field-of-view [FOV] is, in the case of skull examination, 250 mm. Thus, the volume element or the voxel is approximately 0.5 mm×0.5 mm×1.5 mm.

(2) *Segmentation.* A technique called "Segmentation" is applied via thresholding of CT numbers to differentiate various body parts such as bone, tissue, and fat. Segmentation can be considered a process of tissue characterization based on the CT numbers. Thus the background is matted to black and the outer edges are blurred to remove skin if so desired. The original CT images are now segmented and prepared for further processing for display in accordance to the tissue characteristics selected by the user.

(3) *Formation of binary volume.* As described in (1), the voxel is approximately 0.5 mm×0.5 mm×1.5 mm in size. In the axial direction, interpolation is applied so that there are pseudo slices to fill in the gap between the slices that are actually acquired in the original CT scans. The image volume with voxel size of 0.5 mm×0.5 mm×0.5 mm cube is then obtained for further processing.

(4) Grey scale volume via 3-D direct interpolation. Many CT scanners that are equipped with its own minicomputer which has sufficient computation power and can be employed to handle the mathematical operations described in (1)

through (3) including the subsequent operations to be discussed later. However, in order to construct the direct grey scale volume through 3-D direct interpolation, a totally different kind of minicomputer designed for graphics oriented operations may be more desirable. Such graphics oriented hardware has been made available by PIXAR Corporation of San Rafael, California and CEMAX Inc. of Santa Clara, California. The grey scale volume is very much similar to the binary volume, however, each voxel is addressable by the computer for display in accordance to its CT number. The advantage of volumetric rendering will be pointed out later in this article with examples.

While it is beyond the scope of this paper to discuss the details of the hardware configuration employed for the CT scanners or, the PIXAR system [or the CEMAX system] and the software that drive these systems, it is sufficient to follow the chart depicted in Fig. 1 to grasp the simplified view to understand the overall process of the 3-D imaging. The processes (1) through (4), discussed in the previous section, are listed in the left one third of the chart in Fig. 1. The center column (A) through (E) are the processing algorithms and techniques employed for the 3-D image display.

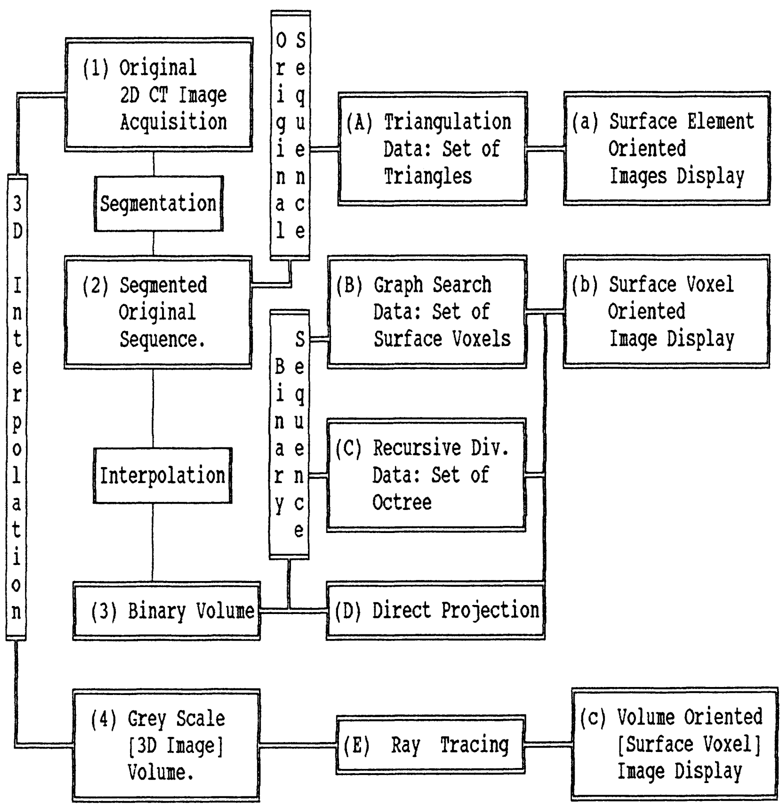

Fig. 1. Schematic Over View of 3-D Image Processing and Surface/Volumetric Rendition. [This figure has been redrawn from a slide presentation provided by Philips Medical Systems, Inc., Shelton, Connecticut, U.S.A.]

The resultant images are briefly described by the right most column in boxes (a), (b), and (c).

Sample images [drawings] based on these three 3-D image rendering are shown in Fig. 2; the triangulation image (a), the surface rendering voxel image (b), and the volumetric rendering image (c) are shown in Figs. 2(a), 2(b), and 2(c), respectively.

The center column (A) through (E) shown in Fig. 1 are the processing algorithms and techniques employed for the 3-D image display. The triangulation method (A), for example, can be described as connecting every two successive CT slices with triangles to form the surface along the axial direction. The CT numbers have been predetermined to select only the BONE, or the VENTRICLE so that a non-transparent 3-D image which surface consists of triangles much like animation. The graph search method (B), and the recursive division method (C) are still in the surface rendering category but account for the thickness of the object that forms the surface. The direct projection method must rely on the computation power of the microprocessor, it selects the interested object surface directly from the binary volume. The ray tracing method along with the grey scale volume formation assign a 12-bit number to each of the voxels. Thus the voxels are associated with each of the primary colors and a level of transparency. This method enables the radiologist to see through the 3-D images, and is unique to the PIXAR system.

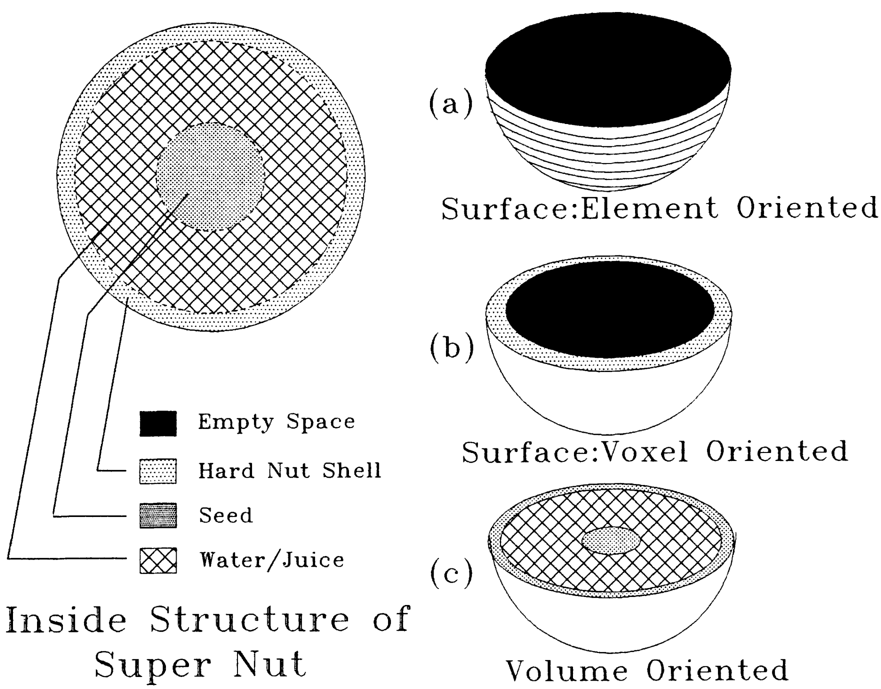

Fig. 2. Sample images of a hypothetical "Super Nut" which has an outer shell, a juice core, and solid core as shown on the left. The differences in the image rendering methods are illustrated in: (a) surface element rendering, (b) surface voxel rendering, and (c) volumetric rendering.

III. EXAMPLES OF CLINICAL APPLICATIONS

This section is intended to list some of the examples of 3-D images employed in the actual patient care. There will be minimum amount of medical information provided, as this article is not intended for medical discussions. The images provided in this section were selected for illustration purposes, only.

III-A. Craniofacial surgery

One of the most successful areas of the 3-D imaging display has been in reconstructive craniofacial surgery. Understanding of the abnormality is the first step toward the reconstructive surgery of the face and skull. Today, in many medical centers, 3-D images are considered essential prior to craniofacial reconstructive surgery. The morphological information provided by the axial CT images and, in particular, 3-D CT images are valuable for the planning of the exact surgical steps (Vannier: 1984).

III-A-1. Depicted in Fig. 3 is the 3-D of skull obtained from CT slices, showing the deformed craniofacial structure of the right orbital cavity. Again, note that this is not a photograph of the skull. For cosmetic reasons, the orbital bone around the right eye [infra-orbital margin and supra-orbital margin] is surgically corrected so that the right side of the facial structure is symmetric [as much as possible] about the center line of the skull.

III-A-2. Depicted in Figs. 4(a) and 4(b) are the 3-D images of an infant. Figure 4(a) was obtained with the "thresholding" set to rendering of bone [skull] to show the skeletal structure. Figure 4(b) was obtained with the "thresholding" set to rendering of skin surface. [Note; This is not a photograph of the patient.] These images were obtained with slice width of 1.5 mm for each axial scan. The CT scanner employed was General Electric CT/T 9800 system equipped with 3-D software. The concentric circular rings seen at the forehead of the infant is the segmentation and interpolation artifact as the axial imaging plane is parallel to the infant's face, in this case. The ventricles of the brain can also be distinguished with these techniques, see Fig. 5.

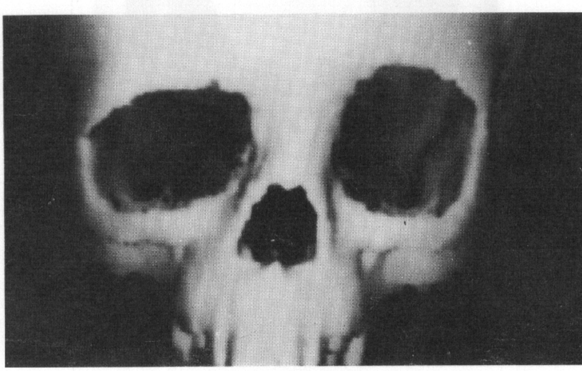

Fig. 3. Example of 3-D craniofacial abnormality [plagiocephaly].

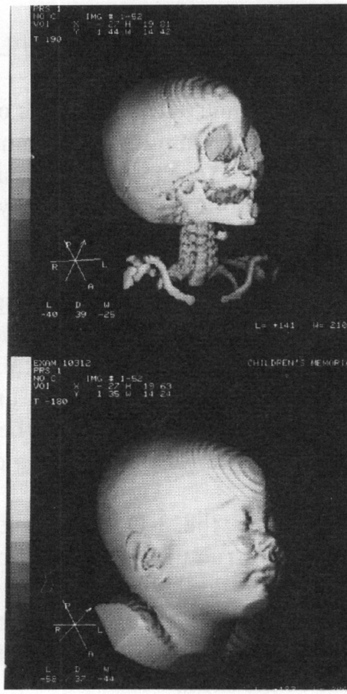

Fig. 4. 3-D image of head and neck. 4(a): skeletal redition,and 4(b): soft tissue rendition.

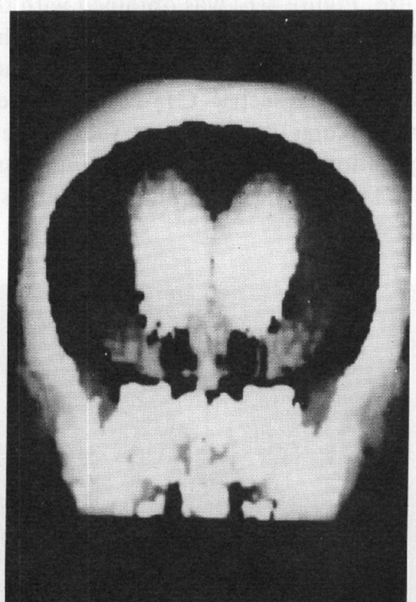

Fig. 5. 3-D image of ventricles using "thresholding" of very low CT numbers.

III-B. Orthopedic surgery

In orthopedics, complex fractures of hip and pelvis can be better understood with the 3-D image display (Zonneveld *et al.*: 1987). The usefulness of 3-D display as applied to acetabular fractures has also been demonstrated (Burk, Jr.: 1985). In addition, many image analysis functions such as ROI [region-of-interest], measure distance, measure angle, etc. that are available under the axial views, can also be made available under the 3-D reconstruction. With those functions available at the finger tips, the fabrication of the prostheses becomes more precise and can be customized for a better fit. Depicted in Fig. 6, is a fractured inferior tibia just above the ankle joint.

The white cylindrical shell-like object surrounding the tibia and the fibula is the cast which has CT numbers close to the bone.

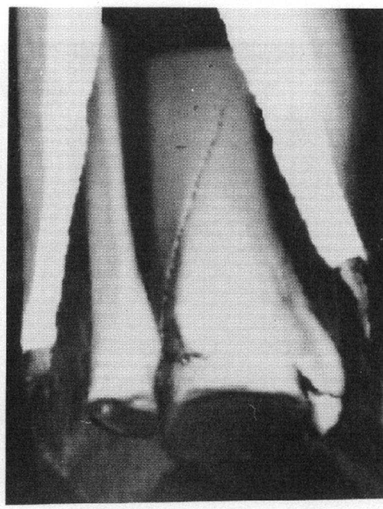

Fig. 6. 3-D image of fractured inferior tibia. The image is cut off just above the ankle.

IV. THE ADVANTAGE OF VOLUMETRIC RENDERING

The images shown in section III belong to the surface rendering category of 3-D image display. 3-D systems employing volumetric rendering are capable of surface rendering image displays. The surface rendering technique is currently available with most CT scanners and the software improvement has made it possible to employ 3-D imaging on a routine basis as the 3-D reconstruction time is in the order of a few seconds rather than several hours. While surface rendering has already proven useful, it is difficult to envision all anatomical parts of interest in the same 3-D display. One can argue that it is possible to superimpose the images separately displaying the 3-D skull image and the 3-D cerebral ventricle image for examples, thus accomplishing the superimposition mentally. Or, color code the cerebral ventricle and display that inside the shell of the 3-D skull image.

In volumetric rendering, the grey scale volume is very much similar to the binary volume, however, each voxel is addressable by the computer for display in accordance to its CT numbers and can be assigned (a) color, and (b) degree of transparency (Giordano: 1987). In so doing, the 3-D image displayed is more realistic than the surface rendering method (Fishman *et al.*: 1987). The ability to assign both the color and the degree of transparency enables the PIXAR system to select and display the anatomy of interest to stand-out or hidden behind in morphologically correct display format.

Depicted in Fig. 7 is a volumetric rendering of the hip muscles with its angled view; at the top section, the internal organs [intestines, bladder] are displayed along with the hip [iliac] bones and the lumbar vertebra. The blood vessels are clearly displayed. Notice that there are faintly shown skin and fat layers covering the volume of muscles shown. The skin and fat layers are assigned to be "transparent".

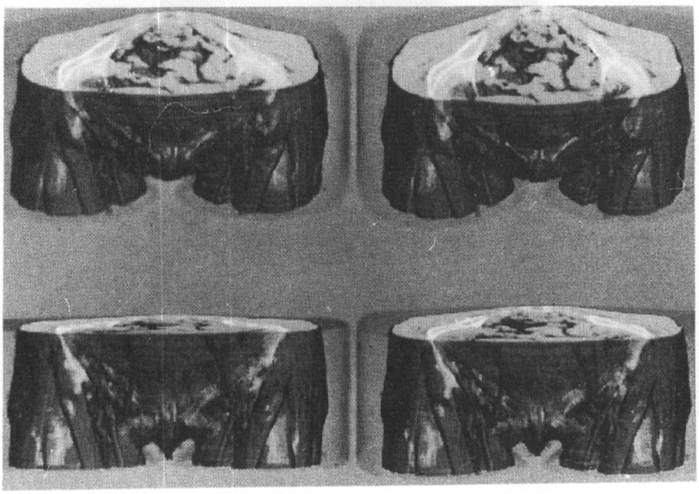

Fig. 7. Volumetric rendering of the hip. [Courtesy of Philips Medical Systems, Inc., Shelton, Connecticut, U.S.A.]

V. DISCUSSION AND CONCLUSION

It has been pointed out that the 3-D imaging is not required for most CT patients and only limited number of patients would require 3-D imaging to gain clinical benefit. Our own study show that approximately 5% of the patients would be prescribed with 3-D imaging either pre or post routine axial scans. Most patients who have undergone 3-D CT scanning route clearly show the indications that the axial scans be geared toward 3-D imaging, i.e., axial scans are performed with slice thickness of 1.5 mm for extremities and inner ears, 3.0 mm for skull, and 5 mm for pelvis thus avoiding the first set of routine axial scans that may otherwise be prescribed with a thicker CT slice width. Routine axial scans with slice thicknesses

3.0 mm and 5.0 mm may still be employed for the purpose of 3-D reconstruction later, with the aids of smoothing software programs. Of that 5% of the patients, approximately 50 to 60% of them really benefit from the 3-D imaging process.

Therefore, keep in mind that only 2 to 3% of the total CT patient population indeed benefit from the advent of the 3-D imaging associated with CT scanners. Surface rendering technique available on the CT scanners provided to the hospitals at a reasonable "software cost" is acceptable if; (1) it requires little training on the part of the operators and (2) time sharing of the CT scanners' CPU [central processor unit] time. However, it is definitely not acceptable if the software is a very expensive option.

This argument may seem critical of the PIXAR and the CMAX type systems that are of independent/stand alone design, and thus there is the cost of the hardware and software involved. However, there are two distinctive advantages with the stand alone type systems. The first is its ability of volumetric rendering [in the case of the PIXAR system] which potential is yet to be explored fully. The second is the fact that it is designed to import any image format whether it is originally acquired with CT or MRI. Therefore, the 2-D images imported from both CT and MRI can be displayed side-by-side on the same PIXAR, or the CEMAX system for comparison. It is also possible to import CT and MRI images acquired with multiple number of manufacturers once the hard format and the soft format of the image tape are licensed.

It is also possible that a dedicated 3-D imaging center can be structured to take in data from multiple number of hospitals, and clinics where 3-D imaging cannot be accomplished either because of time sharing problem or simply lack of such 3-D software that will run on the CT scanners' computer system.

It should also be pointed out that 3-D imaging originating from the MRI is still under development and is not widely available. There is a fundamental problem that mus be resolved before the MR images can be employed for 3-D display. This fundamental problem comes from the fact that the MR images are of low contrast in nature, and the 3-D redering works better with high contrast images such as the CT images.

The full potential of 3-D imaging in MR cannot be assessed properly at this point in time as the 3-D of MR images must first be experienced. Then, the 3-D of CT and MR must be compared and clinical enhancement attained. On the other hand, 3-D MR images may be acquired directly from the three dimensional Fourier transfer [3-D FT] technique within a reasonable time, [say, less than 15 minutes] in the future. Then, the stand alone type systems can be used as an independent graphics work station employed as radiologists tool for image manipulation, freeing the MRI computer for more important tasks of 3-D FT image acquisition and importing CT images for comparison in 2-D or 3-D operations.

The utility and usefulness of 3-D CT images have been shown by many investigators and we have just restated the same in this article. With the completion of MRI 3-D imaging projects currently underway elsewhere, the [MRI] 3-D images of heart, vascular systems, and muscle are expected to enhance the diagnosis of images obtained from CT, and angiographic studies. Improvement of diagnosis in the spinal injury cases and others are expected to accelerate. The future of 3-D imaging and its potential cannot be under stated, we have only began the work that scratched the surface of what 3-D imaging may be able to accomplish that is based on the newly found technological break through.

Acknowledgement

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REFERENCES

(1) Burk, Jr., D. L., Mears, D. C., Cooperstein, L. A., and Herbert, D. L. (1985): Three-dimensional computed tomography of acetabular fractures. *Radiol.*, **155**: 183–186.

(2) Fisher, E. K., Drebin, B., Magid, D., Scott, Jr., W. W., Ney, D. R., Brooker, jr., A. F., Riley, Jr., L. H., St. Ville, J. A., Zerhouni, E. A., and Siegelman, S. S. (1987): Volumetric rendering techniques: application for three-dimensional imaging of the hip. *Radiol.*, **163**: 737–738.

(3) Fujioka, M., Ohyama, N., Honda, T., Tsujiuchi, J., Suzuki, M., Hashimoto, S., and Ikeda, S. (1988): Holography of 3D surface reconstructed CT images. *JCAT*, **12**(1): 175–178.

(4) Giordano, T. A. (1987): A new digital tool for medical imaging, *Intelligent Instruments & Computers*, **5**(2): 67–72.

(5) Udupa, J. K. (1983): Display of 3D information in discrete 3D scenes produced by computerized tomography. *Proc. IEEE*, **71**(3): 420–431.

(6) Vannier, M. W., Marsh, J. L., and Warren, J. O. (1984): Three dimensional CT reconstruction images for craniofacial surgical planning and evaluation. *Radiol.*, **150**: 179–184.

(7) Zonneveld, F. W., van der Meulen, J. C., van Akkerveeken, P. F., Koornneef, L., Vaandrager, J. M., and van der Horst, C. M. (1987): Three-dimensional imaging and manipulation of CT data, Part II: Clinical applications in orthopedic and craniofacial surgery. *Medicamundi*, **32**(3): 99–110.

DISCUSSION

Q. How is your data storage organized? (Brakenhoff, G. J.)

A. In the case of G. E. CT scanners, there are two data sets stored at the time of data acquisition; the raw-data and then the image data. The raw-data is a "first in" "first out" type and is normally partitioned in the hard disk for some 60 raw data space. The image data are the ones, radiologists see on the CRT and achieved for permanent storage. This is also the data set, the 3-D software reads in for 3-D reconstruction. For fast retrieval, the 3-D data sets are stored on optical disks, but need not to be on the optical disk.

Q. Were all the images you demonstrated segmented automatically? (Howard, C. V.)

A. Normally, the images are automatically segmented by a set of pre-determined values that can be altered at will before the read-in of image processing. In other words, there is an option available for user interaction for different "thresholding" and "interpolation".