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Combined Surface Display and Reformatting for the Three-Dimensional Analysis of Tomographic Data

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Radiologic examinations increasingly are based on sequences of cross-sectional images. In current clinical applications, the three-dimensional (3D) relationships contained in these examinations must be inferred by the observer through analysis of multiple two-dimensional (2D) images. In this article, methods for the direct display of 3D gray-level data are investigated. In the chosen approach, the 3D presentation of bone and skin surface serves to orient the viewer, while planar reformation and/or transparent projections can be applied for the assessment of soft-tissue structures in regions of interest. The resulting images represent the original image data in a way that is more suitable for observation of 3D relationships than the conventional cross-sectional viewing mode. This may facilitate the diagnostic process and enhance the interpretability of the images. Routine clinical application of this technique requires special Computer hardware. Research applications, however, can be performed within tolerable times (10-30 sec/view) with computers found in radiologic research environments.

Key words: computed tomography, magnetic resonance, 3Display, reformation, image processing.

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An ever increasing number of medical diagnostic images are obtained from computed tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET), which produce sequences of two-dimensional (2D) cross-sectional slices. The current predominant method of analyzing these images is by sequential observation of individual 2D slices and the viewer's subsequent "mental reconstruction" of these-dimensional relationships. Computerized reformations of CT scans have produced 3D perspective display of bony anatomy that have proved clinically useful in craniofacial surgery and orthopedics[1-9] A general application of this procedure in diagnostic radiology is limited by the fact that only predefined surfaces (mostly bone) can be visualized and that all other information is not used or lost in the reformation process. The classic approach requires a priori knowledge of the grayscale properties of the lesion so that a restricted region for 3D display can be selected. In diagnostic radiology, however, the aim of the diagnostic process is to find and define such regions. Therefore, generally it is impossible to produce a 3D presentation of structures other than bone or skin surface before viewing the original gray-scale images. General diagnostic application of 3D-display techniques requires presentation of the gray scale range for analysis. A few investigations have dealt with the Software and hardware problems of displaying 3D-tomographic volumes that preserve the entire original gray-scale data. Our objective was to study experimentally an approach to 3D reformation of tomographic image data (CT and MR), in which both surface and gray-level data can be presented to the viewer simultaneously.

Materials and Methods

Cranial CT data of two patients were used: for patient l, tomograms of the entire skull were taken; for patient 2, images were taken only around the temporomandibular joint (TMJ). The acquisition parameters are shown in Table 1. The images were then read from magnetic tape to an IBM 3081 computer, and processed by an experimental program written in FOR-TRAN, which was not optimized with respect to speed. This program used the standard software for image processing for earth observation,[14] especially for the geometric transformations. The results were presented on an IBM 7350 Image Processing System. [15]

TABLE 1. Data Acquisition Parameters

CT Images	Patient 1	Patient 2
Organ	skull	skull
No. of slices	80	20
Slice thickness	2 mm	1 mm
Scanner	Somatom DR2	GE 9800
Spatial resolution	256 X 256	512 X 512
Pixel size	0.5 mm	0.2 mm
Intensity range	compressed to 256	compressed to 256

Preprocessing

To save storage space, we compressed the CT values to a dynamic range of 256 gray values. To achieve cubic volume elements ("voxels") we performed a linear interpolation of the intensity values between the original slices. In order to produce a view from a desired perspective, the entire image volume is rotated in the computer memory by resampling the data. Linear interpolation is used for the assignment of the gray-scale values in the resampled volume.

Generalized Projections

The rotated volume now can be viewed by a set of simple "projections" (Fig. 1). Perpendicular to an image plane, the object is scanned until a surface defined by an intensity threshold (bone, outer skin) or a user-specified cut plane of the object is encountered. Depending on the user's specification, new intensity values are computed from the gray levels at or in the neighborhood of the threshold voxel and inserted at the corresponding position in the image plane. The image obtained can be considered as a generalized projection of the object onto this plane.

This procedure differs from classic tomography in that a single image can contain more than one kind of pictorial representation. If this representation is displayed only in gray scale, image ambiguities may occur. For example, the meaning of a certain shade of gray depends upon its location within the image. The assignment of a unique color to the different constituents of the image, such as cut planes or object surfaces, helps to ensure an unambiguous perception of the image. The following basic projections have been implemented and tested.

Projection of Cut Planes

Here only the gray values in the chosen plane are used to produce a new tomography image. This is the same as conventional reformatting and will therefore not be described in more detail (Table 2, case 1).

Projection of a Surface

The computationally least expensive way of projecting a surface onto an image plane is depth shading, the computation of the inverse of the distance to each surface voxel (Table 2, case 2). For a more realistic impression of the surface, shading methods (gradient shading) that take the surface inclination into account have been developed.[3] In our implementation, gray-scale data are used to produce surface shading based on the partial volume averaging effect. The gray values in the neighborhood of the surface voxel are used as a measure of the relative volume of adjacent tissue types (air/ skin, soft tissue/ bone) within the voxel. These relative volumes are related to the surface inclination (Table 2, case 3). This method has been used in this study (Figs. 2, 3, 4). The shading method ("gray level gradient shading") is described in greater detail elsewhere.[16,17]

Transparent Projections

In Gases in which the region of interest is not within a single plane, we can use an imaging mode similar to the classic x-ray projection. The intensity value in the image plane is computed by summing up the gray values in a certain range of the projection ray (Table 2, case 4). In contrast to the classic x-ray technique, we can chosee which spatial range (depth) and/ or intensity range is to be included in the projection. For example, we can include soft tissue only until bone is encountered along the projection ray (case 5 in Table 2).

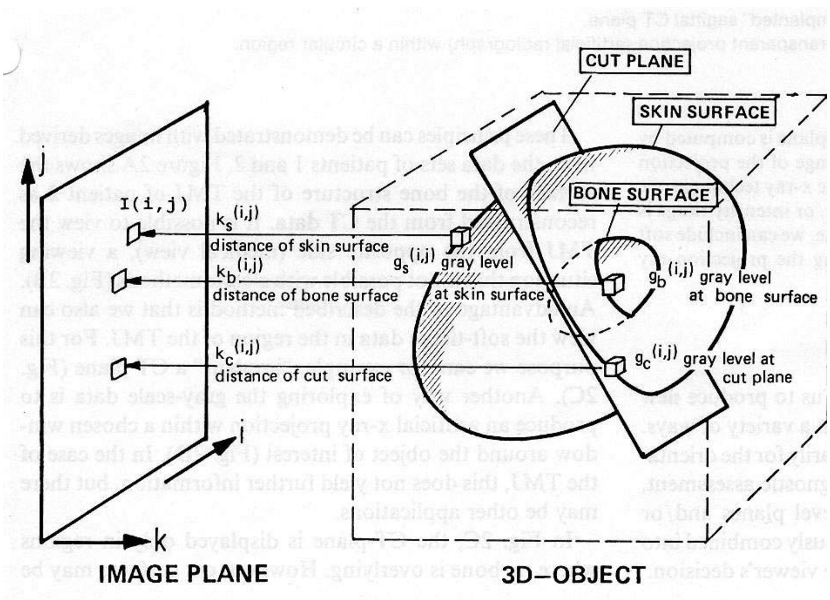


Fig. 1. Schematic drawing illustrating the different parameters used for the projections.

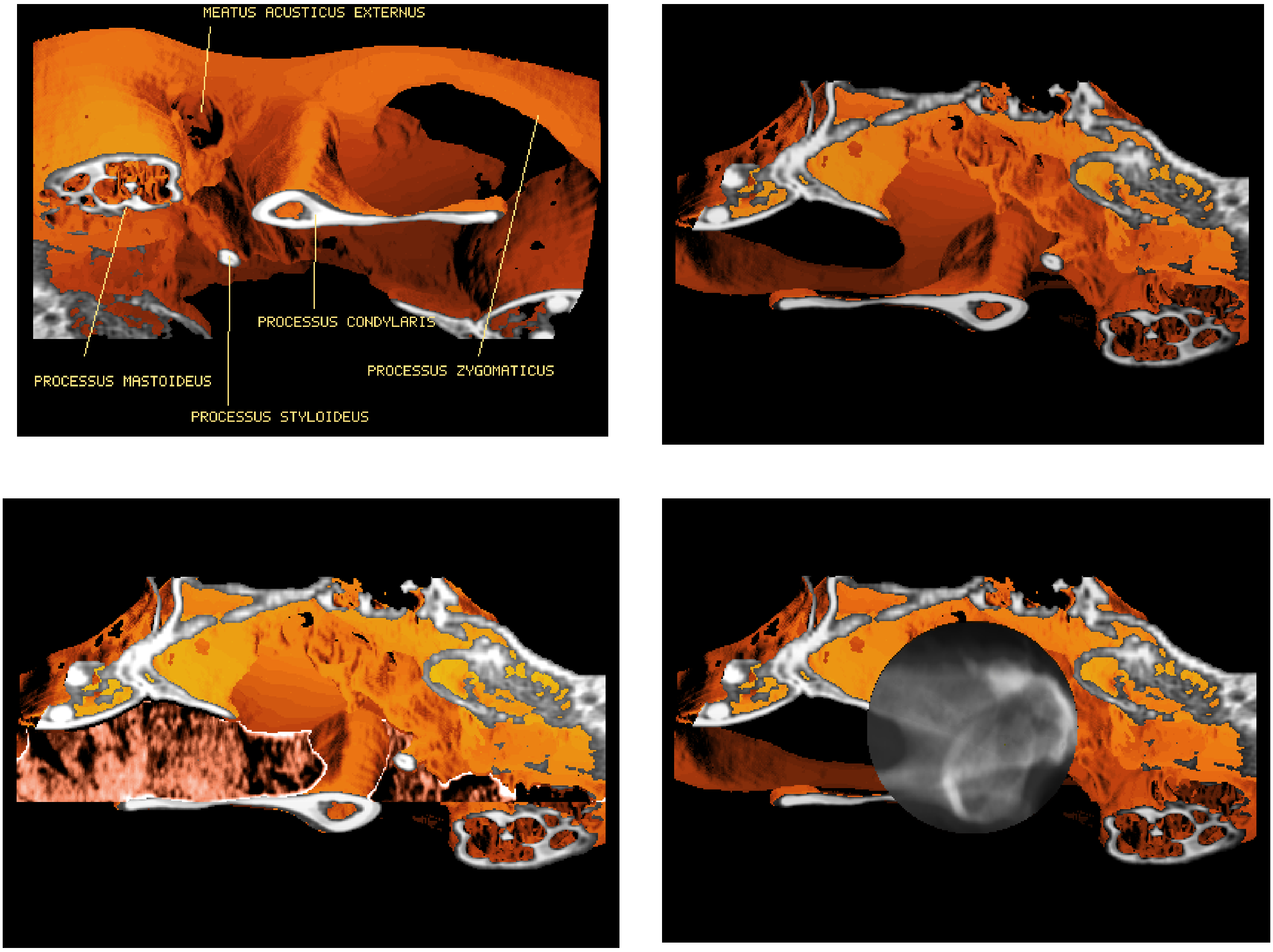


Fig. 2. Surface display of a portion around the TMJ produced from the 20 CT slices of patient 2.
(A, top left) 45° lateral view.
(B, top right) 45° medial view (rotation by 180)
(C, bottom left) Same view as (B) but with "implanted" sagittal CT plane.
(D, bottom right) Same view as (B) but with transparent projection (artificial radiograph) within a circular region.

Results

This procedure is unique in enabling us to produce new images by combining these projections in a variety of ways. Skin or bone surfaces are displayed primarily for the orientation of the viewer in 3D space. The diagnostic assessment, however, can be performed on gray-level planes and/or transparent projections that can be variously combined into this coordinate system, according to the viewer's decision These principles can be demonstrated with images derived from the data sets of patients 1 and 2. Figure 2A shows the surface of the bone structure of the TMJ of patient 2 as reconstructed from the CT data. It is possible to view the TMJ from the opposite side (medical view), a viewing situation that is not possible with classic methods (Fig. 2B). An advantage of the described method is that we also can view the soft-tissue data in the region of the TMJ. For this purpose we can, for example, "implant" a CT plane (Fig. 2C). Another way of exploring the gray-scale data is to produce an artificial x-ray projection within a chosen window around the object of interest (Fig. 2D). In the case of the TMJ, this does not yield further information, but these may be other applications.

In Fig. 2C, the CT-plane is displayed only in regions where no bone is overlying. However, cut surfaces may be displayed regardless of their gray-level structures (Fig. 3A), This image further demonstrates the versatility of the method by displaying the bone or skin surfaces in different regions in the same image.
Another possible combination of the projections is shown in Fig. 3D; the soft tissue in front of the bone is shown as an artificial x-ray, whereas the bone itself is visible as a surface. These images can be used to assess the correlation between bone anomalies and soft-tissue shape. Various other combinations of projections remain to be explored.

TABLE 2. Combined Surface Display and Reformatting for the 3D Analysis of Tomographic Data

Mode	Algorithm	Effect
Cut surface	$I(i,j) = g_c(i,j)$	Gray levels at the cut surfaces are displayed
Object surface (depth shading)	$l(i,j) = 255 - k_s$	3D impression of a surface is achieved by displaying the negative distance to the image plane
Object surface (gray level gradient shading)	$l(i,j) = f\left((\sum_{1=-1}^{+1} \sum_{m=-1}^{+1} (g(i+l, j+1, k_s+m) - g(i+l, j-1, k_s+m)) \right)$	A more realistic surface presentation is achieved by using the gray level differences in the neighborhood of the surface voxel (see (9)).
Transparent projection	$l(i,j) = \sum_{k=k_s}^{k_e} g_k$ where $k_e =$ distance to the end of the object space	x-ray-like image is produced by summing up the gray values within the range of the projection
Transparent until bone	$l(i,j) = \sum_{k=k_s}^{k_b} g_s$	x-ray-like image is produced from tissue in front of bone only

Summary of the different modes of generating new images by different projections. The letters are explained in Fig. 1.

Movies

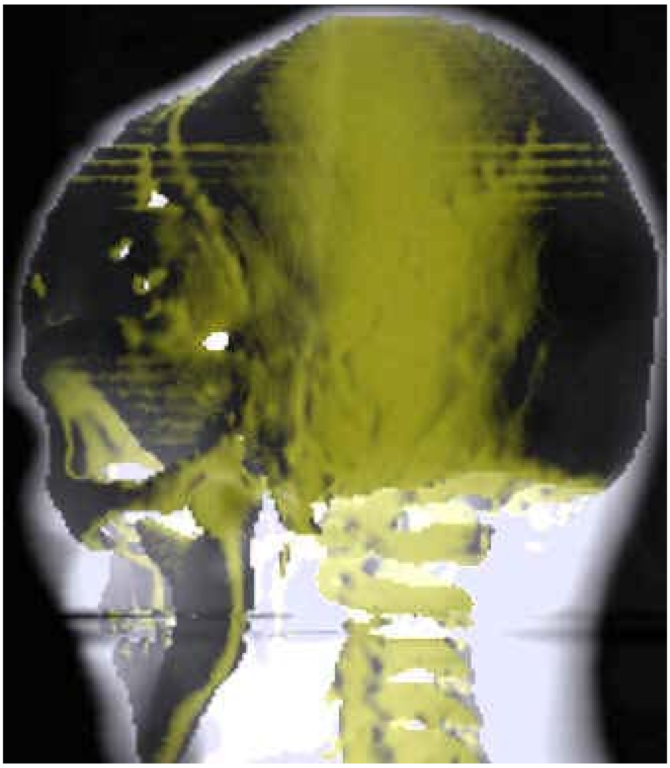
When these operations are applied in fast sequence, movies that enhance the 3D impression can be produced. Rotation in 3D space ean be displayed with inclusion of cut surfaces, implanted surfaces, and projection windows. Figure 4 shows a movie image sequence of 45° sagittal cut surfaces moving through the head of a patient. The spacing of the cuts can be Chosen by the viewer. An impression of a continuous resection can be produced by choosing contiguous cuts.

Discussion

Relevance for Radiology

Until recently, radiology was restricted to planar images of 3D objects. This restriction was due to technical limitations rather than radiologic needs. Now we can generate 3D Images of bony structures, a technique that is used increasingly in craniofacial surgery and orthopedics. The method presented in this article extends the existing technology, applying it to diagnostic radiology so that we can view cross-sectional gray-level image sequences in three dimensions. Once the 3D context of the outer surface and / or bone is available for orientation we can "navigate"visually within the object without having to rely upon a mental 3D reconstruction. This technique allows us to select the optimal orientation and imaging mode after image acquisition. Instead of being constrained to parallel planar images, we can choose our viewing perspectives according to the anatomy and the question to be answered. By displaying the views in fast sequence, we can enhance the 3D impression. Thus, these modes of presentation can improve diagnostic interpretation by improving the observer's perception of 3D anatomic relationships.

For CT, the described viewing methods will be restricted to special cases because of radiation dose limits. With MRI, however, we will be able to generate 3D data sets within reasonable times, and therefore will require new viewing techniques. An experienced interpreter may not need such support for romine studies, but may find it valuable in special cases in which a lesion is obscured by overlying structures. For less experienced viewers and for teaching purposes, the availability of images such as these would be helpful. The question of whether this approach will become a standard radiologic technique can be answered only by continuous radiologic technical research.



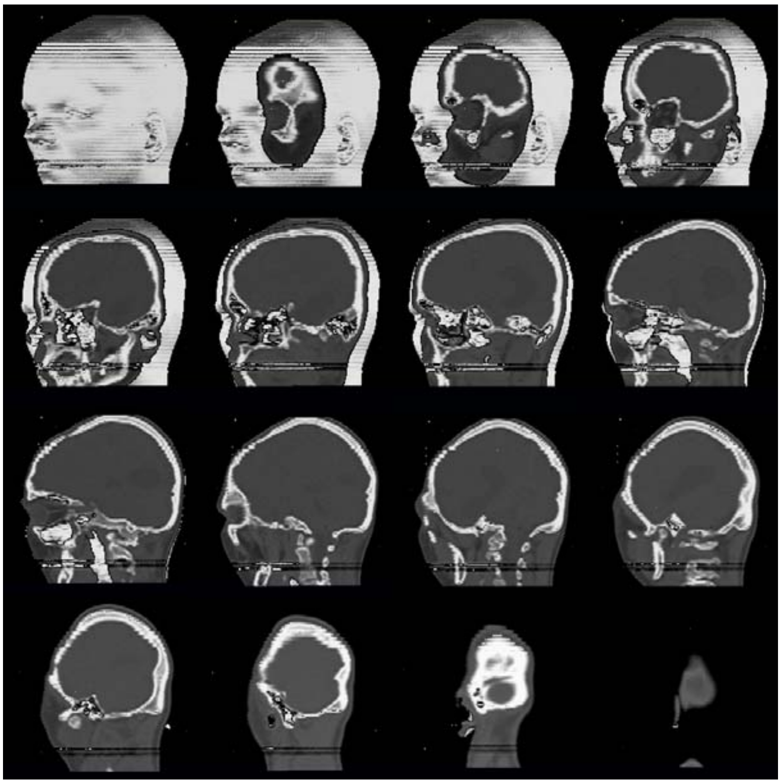


Fig. 3. Combined display of different projections within a single image of a head (patient 1).
(A, top left) Sagittal cut, where display of outer skin surface, bone surface and reformatting has been used in different regions.
(B, top right) 45° dorsal view, where soft tissue in front of bone is displayed transparent, while bone is shown as surface.

Fig. 4 (left). Example for a dynamic display; consecutive presentation of cut surfaces as a movie

Technical Approach

For a clinical application, the major technieal problem involves the achievement of sufficiently high speed for an interactive operation.In pure surface display, a variety of data structures can be used for the fast manipulation of 3D objects.[1,3,7,18] If we want to rotate a gray-scale object for inspection without knowing its structure (eg, surfaces), we can choose between two methods: (1) compute the intensity values in the image plane from the original data whenever we make a projection, or (2) rotate the CT volume once and simply scan lines or columns of the rotated matrices for the projections. The first technique is used effectively in most methods displaying surfaces only, since the original data are generally compressed to binary data describing a surface only. In some cases, further compression is applied.[1] When we deal with gray-level data we are confronted with at least eight times more information (eight bits instead of one bit/voxel). In such cases, the second approach has proved more effective in our study. For inspecting the gray-level information inside the object, three or fewer viewing directions are sufficient. The object can then be explored through simple variation of the projections.

For the object rotation, the image volume must be resampled (interpolated) when new perspectives are produced from the original image data. New voxels are created and gray-scale levels are assigned by resampling methods. Three common methods of resampling are (1) "nearest neighbor," (2) bilinear, and (3) cubic convolution resampling.[14] We chose linear interpolation because the "nearest neighbor" method delivers "blocky" images, and cubic convolution causes intensity overshoots and is computationally more demanding.

In the experimental environment, the rotation of a volume of 256^3 voxels took about 10 minutes. The projections took between 10 and 30 seconds each. We have calculated that these times will not be exceeded with computers incorporated in current MRI devices when the program is optimized.[19] These times are certainly not sufficient for daily clinical work, but could be tolerated in a research environment. For routine clinical applications, more pow-erful hardware is necessary. However, we believe that hardware solutions should not be implemented until studies such as this have determined which operations are really useful. Trivial properties, which the user might find useful, may not be included in the system. As a simple example, a hardware solution that would not allow independent control of intensity level and window in the different (irregular) regions of the images would not be clinically useful.

The speed problem will be solved, but the problem of designing a man-computer interface that would enable a radiologist or technician to take advantage of the capabilities we have described is more difficult. The vast choice of parameters makes the operation unwieldy. For now, simplicity of operation can be achieved only if we restrict ourselves to predefined procedures. Here, we rely on advances in interactive computer graphics research, which we hope will provide tools to facilitate these methods.

In this study we were limited to a CT dynamic range of 256 gray levels (eight bits). The rapid development of computer hardware will allow a greater dynamic range (1,024 gray levels and more). Furthermore, data from multiple parameters within a modality (eg, MRI) or multiple modalities (eg, MRI and CT) can be assigned to each voxel and 3D display generated. In the case of MR alone, the only problem will be storage space. For the combination with CT images, however, our experience shows that the registration requires a high degree of assistance by the radiologist unless special measures for calibration are taken when the data are collected. This presently limits the possibilities of combined MRI and CT display.

We have demonstrated a method of viewing 3D tomographic data that uses 3D skin and bone surface display for the viewer's orientation, while planar reformation and/or transparent projections can be applied for the assessment of soft tissue structures in regions of interest. Instead of being constrained to parallel planar images, we can 'navigate' within the 3D surface and bone anatomy and choose optimal viewing conditions according to the anatomic environment. The described software solution is not yet fast enough for routine clinical application. For research application, however, the processing time (10-30 sec/ view) with computers found in radiological research environments is tolerable. For a final specification of clinical hardware solutions, further research of the kind described is necessary.

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