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A Computerized Three-Dimensional Atlas of the Human Skull and Brain

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PURPOSE: To develop an anatomic atlas of the human head based on a volume model derived from MR and CT. **METHODS:** Every voxel of this model was labeled by a neuroanatomist concerning its membership to a structural and/or functional region. A computer program was written that, instead of displaying precomputed images, allows the user to choose and compose arbitrary views. **RESULTS:** The user can subtract parts and ask for annotations just by using the mouse. Conversely, one can compose images by choosing objects from the list of anatomical constituents which is displayed on the screen. A set of dissection tools allows a "look and feel" that comes near to a true dissection. Operations that are not possible in a real dissection, such as reassembly or filling cavities, can be performed. **CONCLUSION:** The authors have developed a computerized model that can be used for anatomy teaching and also as a reference for radiologists or surgeons. To replace classical atlases, the spatial resolution must be improved and speed must approach real time. Functional imaging data (position emission tomography and single photon emission CT) can be added to the system. The system is mobile and can be situated in classrooms, operating rooms, reading rooms, and libraries.

Index terms: Skull, anatomy; Brain, anatomy; Computers, software; Teaching aids

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Recently, it has become possible through the methods of digital image processing and computer graphics to reconstruct from magnetic resonance (MR) imaging or computed tomography (CT) the shape of anatomic objects in three dimensions (1-5). Such reconstructions have proved to be useful in therapy (especially surgery) planning (6-8). However, widespread application is limited by a problem peculiar to three-dimensional image processing: unlike the situation with two-dimensional cross-sectional images, objects within a three-dimensional scene may obscure each other. Therefore, any visualization must be preceded by a segmentation step in which three-dimensional regions belonging to an organ must

be identified. Only if this is done can they be visualized or removed. This segmentation step is the most difficult one in 3-D visualization. At present, only very few objects can be segmented automatically. The educational application of 3-D visualization techniques has been overlooked. In this case, only a limited number of specimens have to be segmented into their constituents; it is feasible for this work to be done by a person rather than by a computer. With this motivation, we have developed an interactive 3-D atlas of the human head. It is the purpose of this paper to show the usefulness of this approach both for education and clinical work.

Materials and Methods

Basic Data

The basic idea is to describe the anatomy in two levels (Fig. 1). The lower level is a volume data set from cross-sectional imaging such as MR imaging and/or CT (pictorial level). In addition to an intensity value, each volume element contains attributes describing its membership to basic regions. There are different kinds of basic regions depending on the feature considered, such as: structural regions (eg, the precentral gyrus of the brain); functional regions

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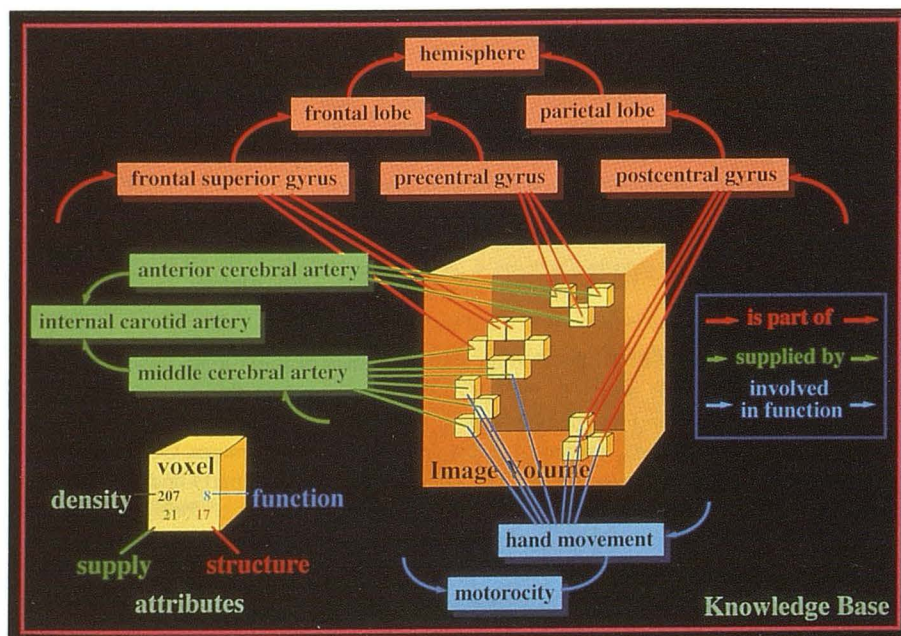
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Fig. 1. Structure of the three-dimensional anatomical model. Each voxel of the basic volume bears, besides a density value, an attribute describing its membership to a basic region (pictorial level). Relations between the basic regions are described in the knowledge base (descriptive level).



(such as the sensorimotor cortex); and regions supplied by a given blood vessel.

The upper level is a knowledge base that contains *relations* between the basic regions (descriptive level). These relations may concern: structure (eg, precentral gyrus is part of the frontal lobe); function (eg, a sensory stimulus goes through the spinothalamic tract); blood supply (eg, the internal carotid artery supplies the anterior cerebral artery and the middle cerebral artery); and topology (eg, the thalamus is next to the third ventricle).

Construction of the 3-D Head Model

As a basis for the pictorial level, we use an MR image and a CT data set of a head as basic image volumes. The original cross-sectional images are interpolated to achieve an image volume with cubic voxels. This is performed by linear scaling in the direction perpendicular to the original slices. The resulting MR imaging volume contains $150 \times 200 \times 192$ voxels with a width of 1.5 mm. The CT volume contains $240 \times 222 \times 246$ voxels with a width of 1 mm.

The most critical step is the assignment of the anatomic knowledge to the image volume. This is done in several steps. Initially the gross constituents, such as skull, brain, and ventricular system, are segmented by an interactive segmentation program. An expert selects the appropriate regions using the intensity window control and special image processing tools (9–11). The subdivision of the coarse components into detailed structural regions (like the gyri) is done by the neuroanatomist using a "volume editor." For example, a gyrus would first be identified by painting its extent on the 3-D brain surface image. The gray matter (voxels below the painted surface) is included by specifying an intensity threshold. Refinements can now be made by repeating the painting procedure from different viewing angles and finally on the cross-sectional images. Although

we have developed a set of special tools, this labeling step is tedious. The final step is naming the identified regions.

Once the image volume is labeled in the described way, the relations between the basic regions are entered into the descriptive level of the knowledge base. Two hundred basic structural regions have been labeled and their structural relations are stored in the knowledge base. In addition, the data base contains the paths of the major tracts and the sulci, which can be visualized as polygonal lines in 3-D space.

Exploration Tools

The tools for the exploration of the acquired head model may be divided into four groups: visualization, composition, exploration, and simulation. For *visualization*, computer graphics provide all effects that a painter would use to paint a 3-D scene onto a planar screen. Depth impression is produced by obscuration and by perspective parallax. Proper impression of shape is achieved by simulating light reflection from the surfaces according to surface inclination and reflectivity. In this context, highlights play an important role. To achieve all this, we use tools that we have developed in previous projects (12). A viewer can generate arbitrary perspective views by choosing, for example, a certain viewpoint or light direction. Cutting tools are provided to reveal interior structures. The user may move a plane in any position and direction (Fig. 2) in order to specify a cut. He may repeat this procedure in order to dissect the head in various sections. A particularly useful feature is selective cutting, which excludes objects from cutting. The colors are chosen arbitrarily.

In the *display composition* mode, components may be displayed via selection of objects from the list of names in the knowledge base, such as: add/remove objects (eg, a gyrus); paint objects with a chosen color; and show objects involved in a certain function.

In the *exploration* mode, the visible image can be explored by pointing on a region of interest according to the location of the cursor on the visible 3-D surfaces or cut planes. New images can be created, for example, by coloring the chosen region, coloring parent regions (eg, the lobe to which a gyrus belongs), removing a chosen region, or adding an object with a certain relation to the selected one (eg, in front).

Output of text that can be associated with the displayed objects can also be created, such as: annotating the object, listing the parent names, and displaying the description attached to the object.

Finally, application-oriented tools for the *simulation* of medical procedures can be derived from the basic tools. Three of them are presently available: simulation of craniotomy, simulation of the path of a stereotactic device, and simulation of x-ray images from computer tomographic volumes.

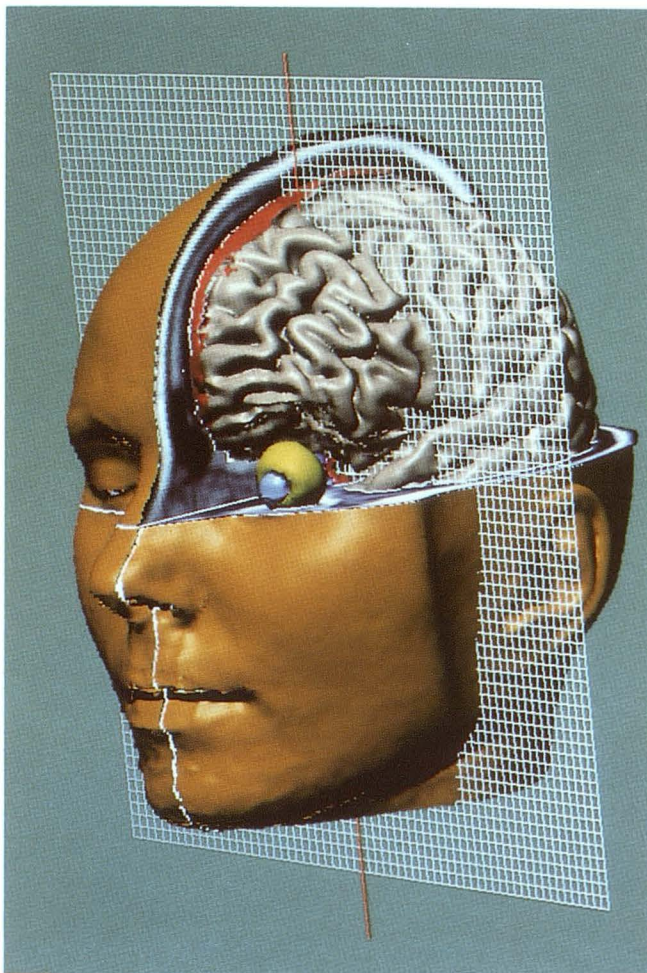


Fig. 2. Dissection of the head model at the computer screen. A wire mesh is used to define cut planes. Within the sections generated this way, objects can be removed, providing the look and feel of an actual dissection.

The program is implemented in the C programming language under the UNIX (Bell Laboratories, Murray Hill, NJ) operating system using the OSF/Motif (Open Systems Foundation Inc.) standard for the user interface. With these standard tools, it is running on standard UNIX-workstations as they are used in connection with state of the art MR and CT devices such as DECstation 5000 (Digital Equipment Corp., Maynard, MA), IBM RS/6000 (International Business Machines Corp., Armonk, NY), and SUN SPARCstation (SUN Microsystems, Mountain View, CA). The speed of the atlas is vital for practical application. For the most frequently used exploration actions such as coloring or annotation, the reaction time is less than 1 second. For exploration actions such as rotation and cutting, it depends on the quality chosen. The small images in Figure 3 (256×256 image matrix) appear in about 5 seconds on a DECstation 5000/200, a quality that is sufficient in many instances. Development of a high quality image such as the large one in Figure 3 (1017×604 image matrix) may take 10 minutes.

Results

A student could begin to explore the brain model with a skin surface image of the head. As the first step, one could simply cut into the head and explore the appearing section. However, an anatomist would prefer to remove the tissue layer by layer. This easily can be simulated by "selective cutting" as shown in Figure 2. Here cut planes have been specified and the objects "brain" and "eye" excluded from cutting. Since the cut surfaces exhibit the original intensity values, the scene has the appearance of an actual dissection.

The crucial advantage of the computer model is that, for any visible voxel, all related information can be queried. As seen in Figures 4, 5, and 6, the corresponding object names (such as the name of a gyrus) can be annotated at the cursor position, whether there are sections or multiple surfaces or both. The corresponding region can be colored as well. Thus, questions about the nature of the visible objects can be answered easily. The language for the annotations can be chosen (presently available: English, Latin, and German).

Questions about the relationships between basic regions can be answered as far as they are described in the knowledge base. In the pilot project, for example, the structural parents of a basic region (eg, the lobe to which a gyrus belongs) can be queried and colored, displayed, removed, etc. (Fig. 4). A question addressing

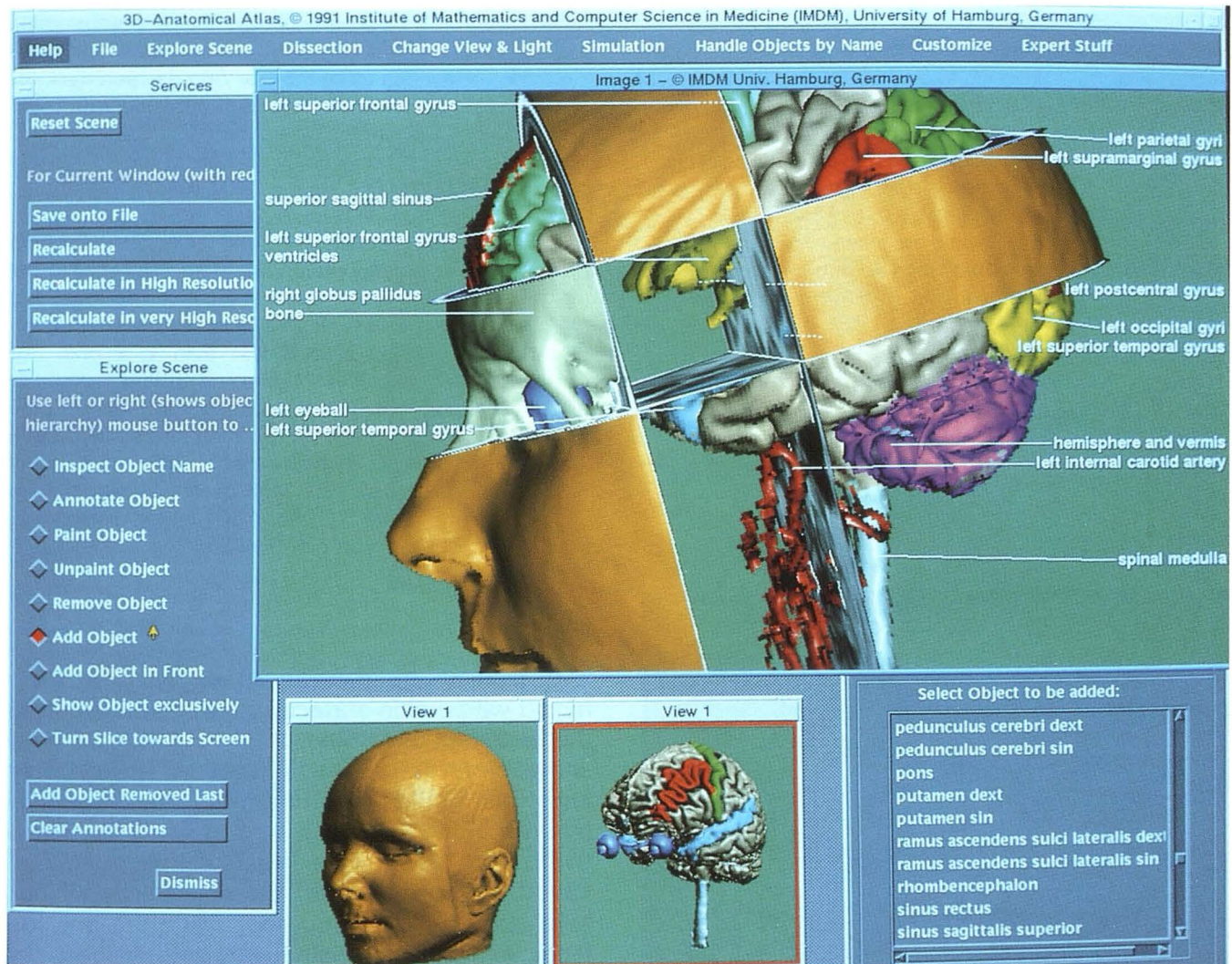


Fig. 3. "User interface" of the atlas. A viewer can address the exploration tools (left) via a mouse and generate annotated views with the desired direction, size, and resolution. Objects to be displayed may be selected from the knowledge base (lower right corner).

topologic knowledge might be "show all neighboring objects."

We can in the reverse case browse through a textual display of the knowledge base and select an object or group of them that can be treated as shown above. For example, we could ask for the exclusive display of the thalamus and neighboring objects as shown in Figure 5. In this case, it is advisable to add the ventricular system for orientation. Unlike in an actual dissection, we can display it as a solid object. While in the previous examples radiologic imagery served for teaching basic anatomy, the same data can be used for teaching and reference purposes in radiology itself. As shown in Figure 5, this can be done by presenting cross-sectional images in the context

of basic anatomy. Whether we are on a section or an object surface, the exploration tools such as inquiry of names can be used.

A structure that is not well represented on MR imaging is bone. Therefore, we derive the anatomy of the skull from a CT data set. Unfortunately, we presently do not have the data sets from the same person. As an example for the use of the skull model, Figure 6 shows the transnasal access to the pituitary gland.

The previously described operations enabled us to explore freely an anatomic object in a style comparable to dissection. Furthermore, the same basic tools can be used for the simulation of certain clinical procedures. We demonstrate two of them as follows.

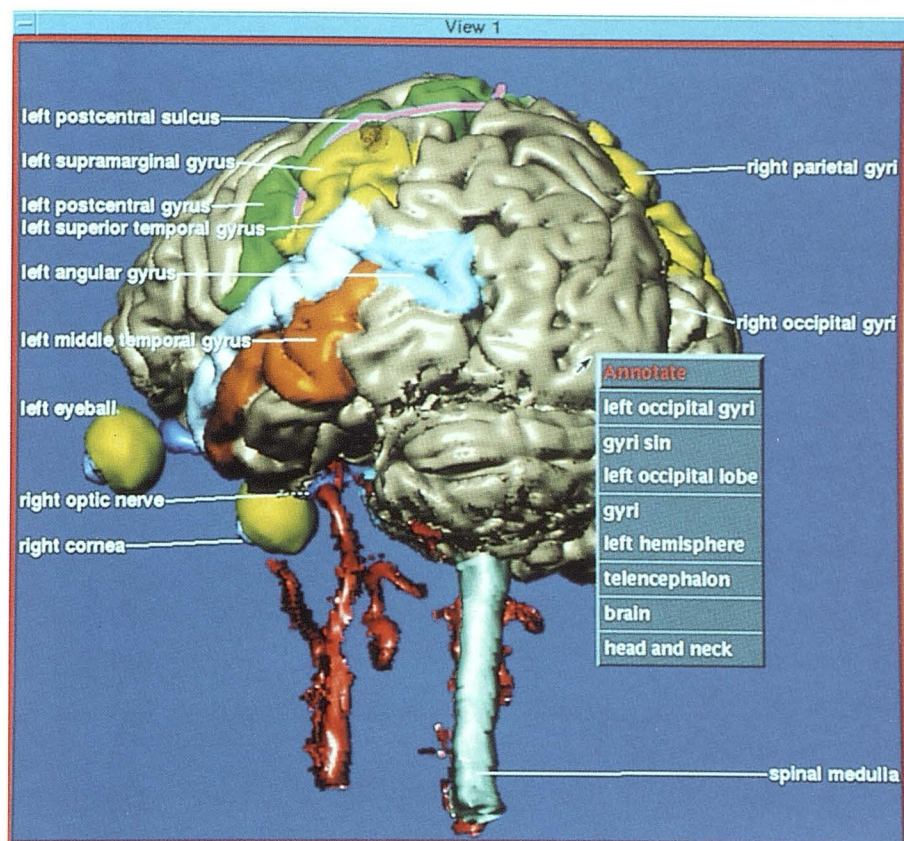


Fig. 4. Views from any direction, such as this oblique dorsolateral one, can be produced. At any instant, for every visible voxel, information such as object names with their parents in the structural hierarchy can be queried (shown in the "pop-up" window). Regions may be annotated and/or colored by a "mouse" click.

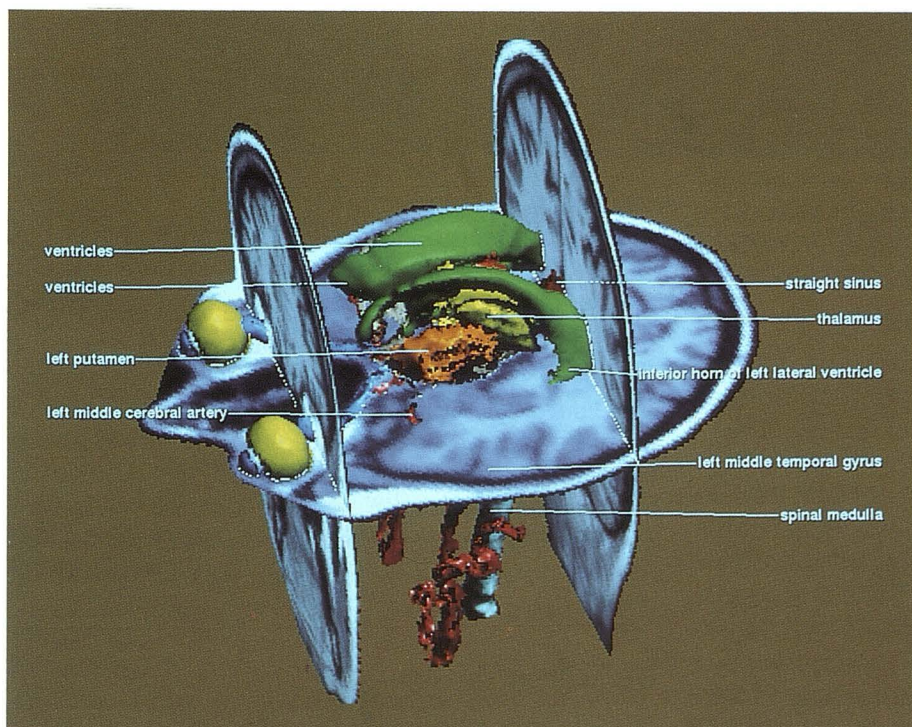


Fig. 5. Integration of cross-sectional imaging with basic 3-D anatomy. Cross-sections and anatomic constituents may be chosen freely by the viewer.

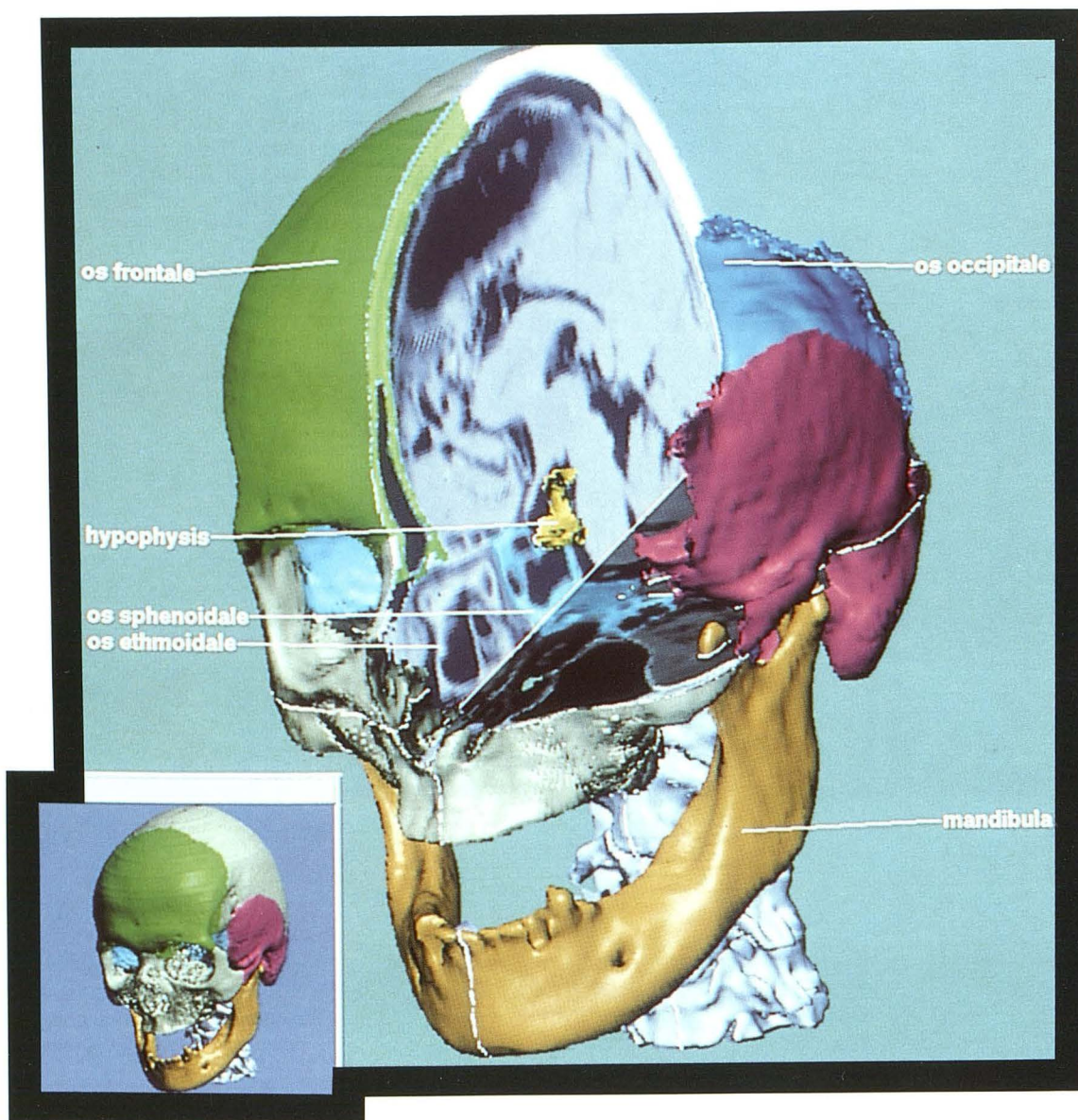


Fig. 6. View showing transnasal access to the pituitary gland.

Simulation of an X-ray Exposure and Neurosurgery Planning

A CT data volume represents the absorption values. Thus it is easy to simulate an x-ray projection from a chosen direction with any beam geometry. Since we know the objects that cause the projection image, we can determine the contribution of the individual objects to the final intensity at any location (Fig. 7). Thus a student can conveniently check knowledge in radiologic image interpretation.

In neurosurgery, it is vital that the access to a lesion such as a tumor is optimal in that it avoids damage to vulnerable regions (like blood vessels

or sensorimotor cortex). With the tools described, surgical operations and stereotactic interventions can be simulated in order to enhance the necessary surgical skills. Figure 8 shows the way a craniotomy can be simulated and the access path to a region of interest explored. As shown in Figure 9, stereotactic surgery can be simulated as well. Objects encountered using a certain needle position and direction can be identified easily.

Discussion

Over centuries, textbooks and atlases were the only media for learning anatomy. With the de-

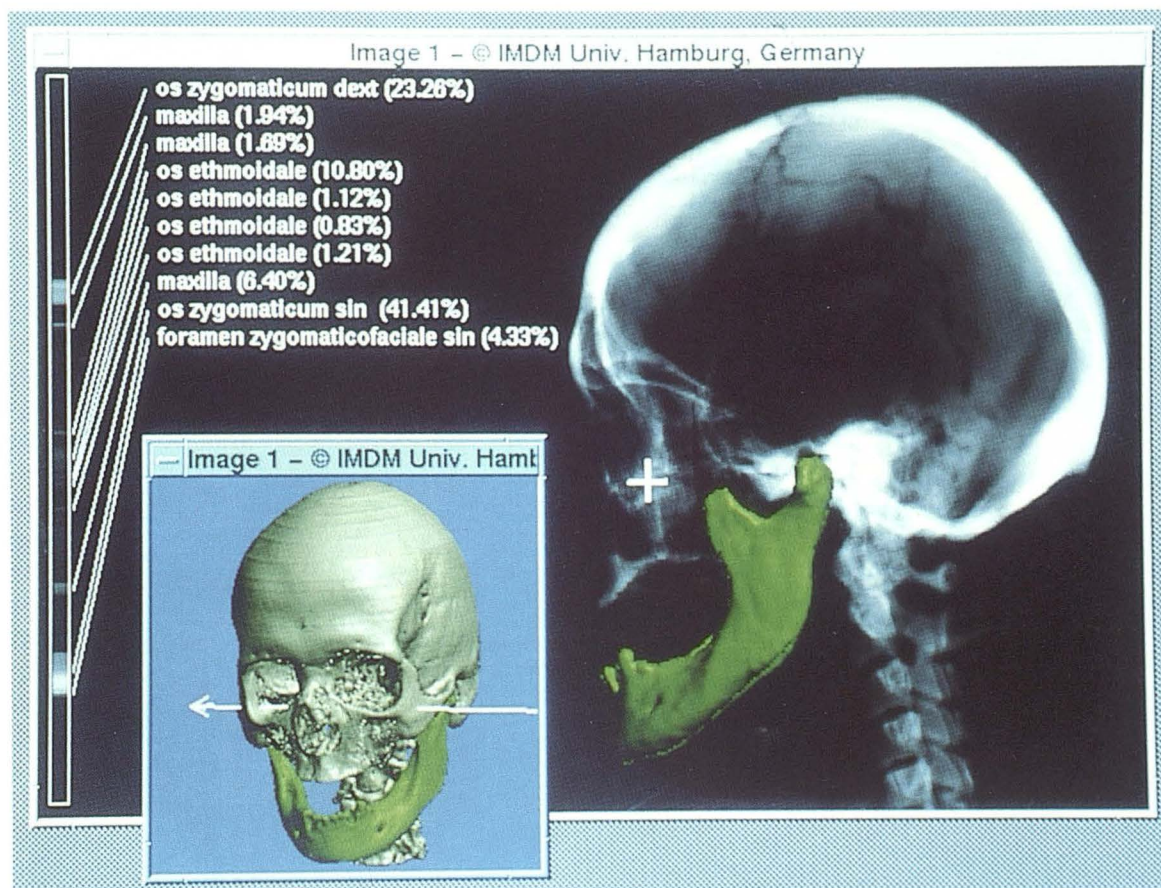


Fig. 7. Artificial x-ray image (topogram) produced from the CT model. At the cursor position, the relative contribution of the components to the final image can be queried. In the inserted localized view the direction of the x-ray beam is depicted. Components (in this instance, the mandible) can be added at their proper location.

velopment of so-called hypermedia techniques in the past decade, both pictorial and descriptive knowledge can be organized in such a way that a learner can browse through the knowledge on a computer screen in a sequence that depends on the teaching aim and individual needs (13). Still the underlying model is that of a book: hypermedia screens mostly exhibit a set of pages, in which the pictures are precomputed or digitized image matrices. Different aspects of the same object have to be available as different images. By having computerized anatomical models of the objects, different pictorial representations can be created at the user's will. Thus it is also possible to integrate a dissection function into a learning program.

Computerized models of the human brain have been used for several purposes in the past. One purpose is the correlation of functional information (eg, from positron emission tomography) with detailed structural information (eg, from MR imaging) (14–16). A more academic application

of a computer model is as a knowledge base for experiments in computer vision. Not much work has been done in the field of model-based atlases for medical education (17–19). The projects described until now have in common the representation of objects as surface layers. They do not allow the “look and feel” of a dissection, which is the main tool of exploring an anatomic object, because the objects are hollow. Cutting thus does not reveal realistic surfaces.

The approach presented here is based on a complete solid volume model. Through the linkage of descriptive information to sets of voxels, a variety of novel applications can be generated. Using state-of-the-art neuroradiologic imaging, it is now possible to generate computer models that allow dissections such as the exploration of human anatomy on a computer screen at any time and location. Thus, one can anticipate moving the dissection laboratory to places it is actually needed, such as the classroom, the examination

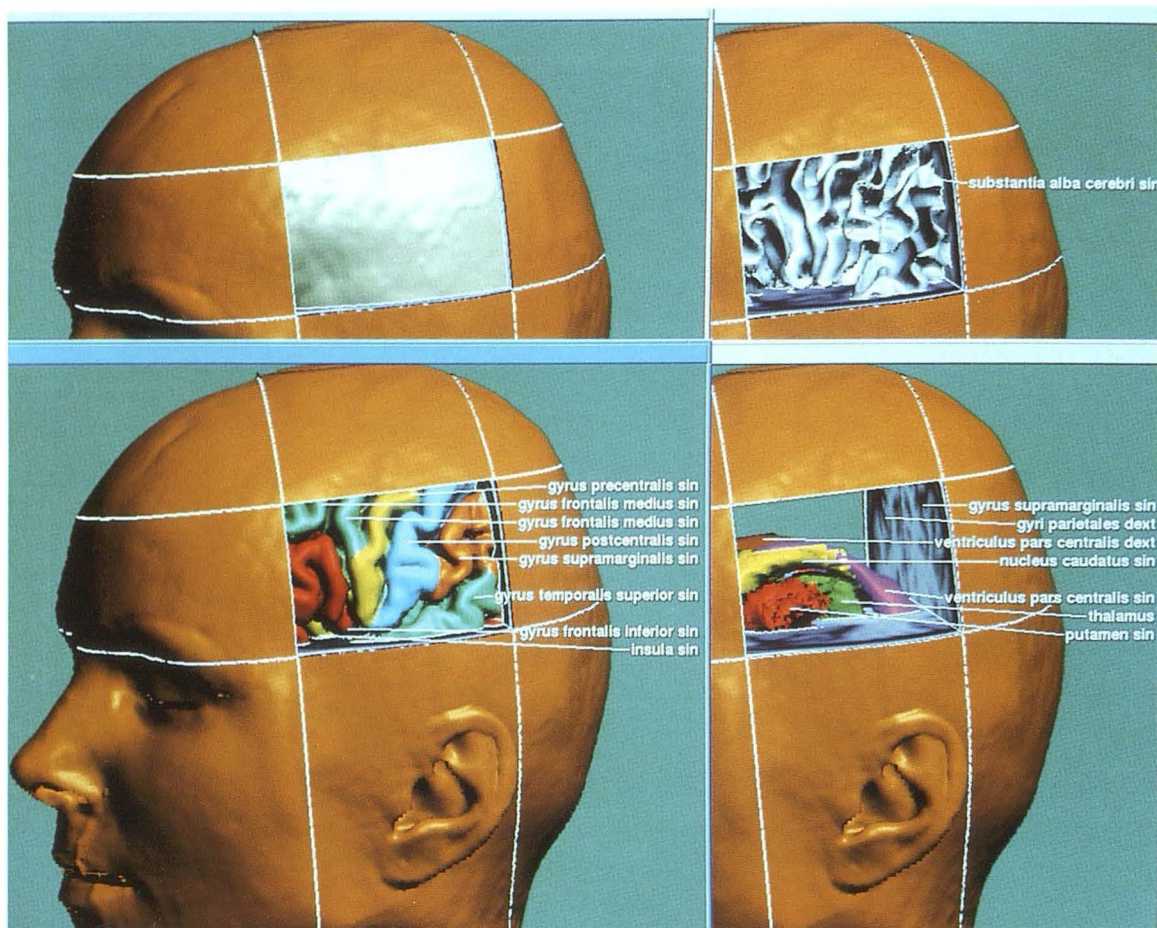


Fig. 8. Simulation of craniotomy. Layers can be removed successively and information queried about the encountered objects.

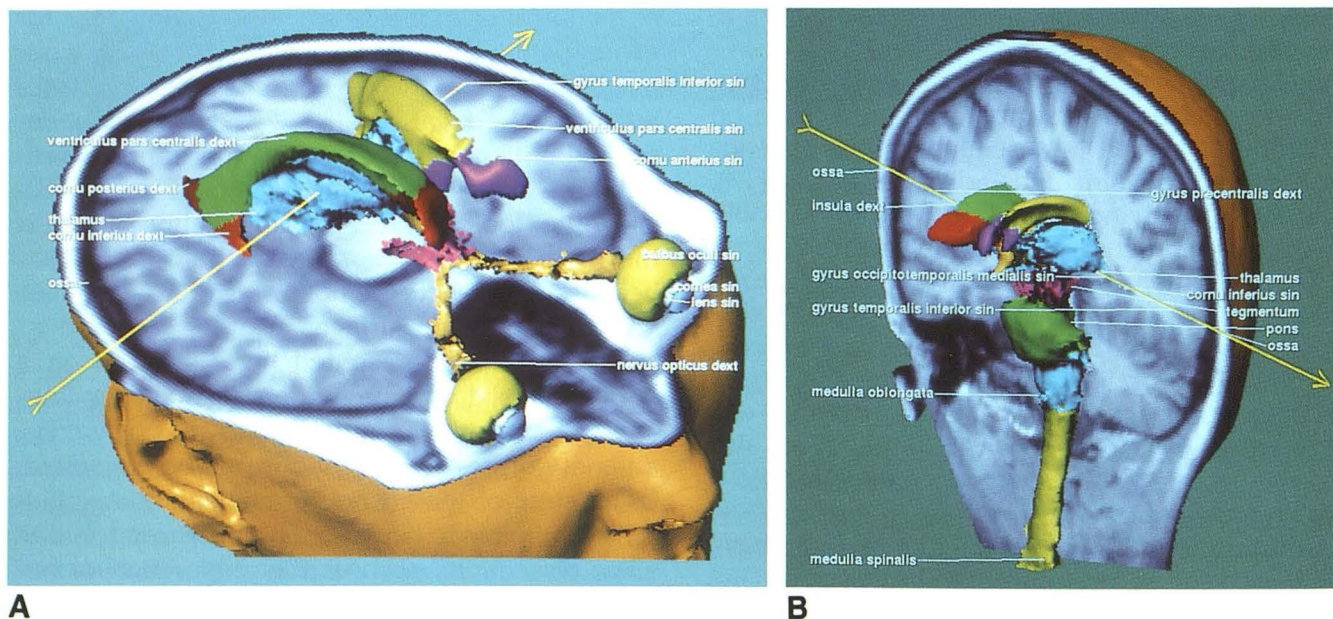


Fig. 9. Stereotactic simulation. *A*, Target (in this instance, the thalamus) and needle direction (arrow) can be defined. *B*, A cut plane along the needle unveils the encountered objects and the puncture site at the skin surface. In this example, the precentral gyrus is involved.

room, the operating room, the x-ray reading room, or the library.

From the technical point of view, the volume model has proved to be a powerful data structure for constructing 3-D anatomic models. On one hand, this is because it is well suited to visualization of both surface and volume properties of the anatomy. It provides some of the look and feel which come near to those of actual dissection. On the other hand, it is flexible in that it easily allows the incorporation of extensions and more details on both the pictorial and the descriptive level. It must be admitted that 3-D editing of the spatial regions is a tedious task, but it need be done only once for a specimen. This can then be used in an unlimited number of copies. The required large computing power will be a less serious obstacle in the near future. A problem still remaining is the construction of a user interface that allows the easy and natural access to the exploration tools and the availability of computer power such that any reaction of the system could be in real time.

The spatial resolution achieved with MR imaging is not yet sufficient for all applications. Nonetheless, the pilot project has shown that an approach based on a solid volume model allows the user to choose, according to personal needs, a virtually infinite number of realistic scenes of the anatomy to be explored. Thus the approach comprises the presently used atlas techniques in that it allows the generation of pictures in a form needed for both books and hypermedia documents. Beyond atlas generation, our approach even allows the generation of real solid models by using stereolithography. For general use, the data base must still be refined. For completeness, image material such as photographic images of cross-sections as representation for the actual anatomy of a specimen, or positron emission tomography for functional aspects, must be included. The described techniques are being used for the construction of models of other parts of the body (abdomen) and specimens (fetus). Their inclusion is not a problem in computer science, but a practical problem of data acquisition.

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