A 'Virtual Body' Model for Surgical Education and Rehearsal

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Neither superhero nor crash-test dummy, Voxel-Man is an attempt to combine in a single framework a detailed spatial model enabling realistic visualization with a symbolic model of the human body.

Computer support of surgical interventions has become a major research area in recent years. Development began with the first attempts at pre- and postoperative 3D visualization of bone structures from computer tomograms. From a stack of consecutive cross-sectional pictures, bone was identified and visualized with early computer graphics shading methods. Thus, rather complex interior structures could be viewed for surgical planning and the results assessed postoperatively. This technique has become standard in several disciplines, for example, craniofacial surgery.

Next, researchers tried to simulate the effect of surgical interventions. This is far more difficult, because in addition to visualization, complex and fast interaction techniques are needed. Recent developments approach the even more complex task of interoperative surgical support.[1] Two- or three-dimensional images are fused with the actual surgical view of the patient to inform the surgeon about deeper structures close to the surgical site. On the basis of this information, the surgeon decides how to proceed.

For the latter procedure especially, we must acquire a spatial model of the patient's anatomy that is as accurate as possible. For this purpose an image volume (a stack of cross-sectional pictures of the patient) must be segmented into its anatomical constituents. Not all important constituents will necessarily be visible; moreover, automatic segmentation is not possible with present-day technology. Interactive segmentation methods are still too time-consuming for broad clinical application. A general digital model of human anatomy is thus very helpful both in supporting the process of segmentation and as a reference system for simulating surgical situations or even rehearsal of interventions. This article describes the data structure and implementation of such a model. We show that although a general model does not correspond in detail to an individual patient, it does provide a variety of novel features for surgical education and training.

EARLIER WORK

The idea of having a digital representation of the human body is not new.[2] The first efforts resulted in databases that enabled retrieval of relevant items for a limited part of the anatomy. These systems were mostly local solutions that enabled researchers to archive their own results along with related results described in the literature. Although these databases were an improvement for research, they were deficient in connecting descriptions to anatomical structures and visualizing the stored information in a "natural" way.

The next step was to include the kind of graphics and images that can be found in standard books and atlases, such as the one by Talairach and Tournoux.[3] Usually, multimedia and hypermedia techniques are used to link symbolic with pictorial data. Some of these systems include histological or photographical images from cadaver dissection. On the same basis, teaching programs have also been developed. These systems enable convenient access to different anatomical information, but the stored images are precomputed views, so a "look between the atlas pages" is not possible.

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Digital anatomy representations have also been described that were designed to help interpret images used for clinical diagnosis. In these representations, anatomical structures appear as sets of coordinates or 2D contours only, and the anatomical knowledge is restricted to a (sometimes hierarchical) list of anatomical names for a limited number of morphological objects. Likewise, purely abstract descriptions without a pictorial representation have been described for automatic image interpretation with computer vision techniques. Only a few digital anatomy representations based on a 3D model have been described.[4-6] In these projects, objects are represented as 3D contours only and are therefore unrealistically hollow.

A first step toward acquiring detailed data for a space-filling model is made in Ackerman's Visible Human project,[7] where data on two cadavers is being acquired, respectively, by magnetic resonance (tomography) and computed tomography, and by photographs of anatomical cross sections. The project, a joint effort of the National Library of Medicine and the University of Colorado, has not yet defined a procedure for how to convert the data into an anatomy model.

INTELLIGENT-VOLUME APPROACH

The key idea underlying our new approach is to combine in a single framework a detailed spatial model enabling realistic visualization with a symbolic model of the human body (Figure 1). A pilot implementation has been made for the skull and brain.[8] The spatial model is sampled from a living subject via cross-sectional imaging modalities such as computed tomography, magnetic resonance tomography, or histological sections.

This volume is segmented into its constituents in as much detail as possible. These constituents will differ for the different domains of knowledge, for example, structural and functional anatomy. The same voxel may belong to different voxel sets in more than one domain. The membership is characterized by object labels stored in "attribute volumes" congruent to the image volume (see Figure 1). Further attribute volumes may be added that contain, for example, the incidence of a tumor type or a time tag for blood propagation on a per-voxel basis.

The objects themselves bear attributes as well. These may be divided into two groups: attributes defining an object's visual appearance, like color, texture, and reflectivity; and attributes related to an object's meaning. Attributes related to meaning might include not only names (in different languages) and pointers to text or pictorial explanations, but also features such as vulnerability or mechanical properties that might be important in surgical simulation, for example.

So far the model describes a spatial distribution of objects but not their interrelations. For their description we chose among different possibilities of knowledge representation offered by artificial intelligence, selecting the technique of semantic networks. This allows the expres-

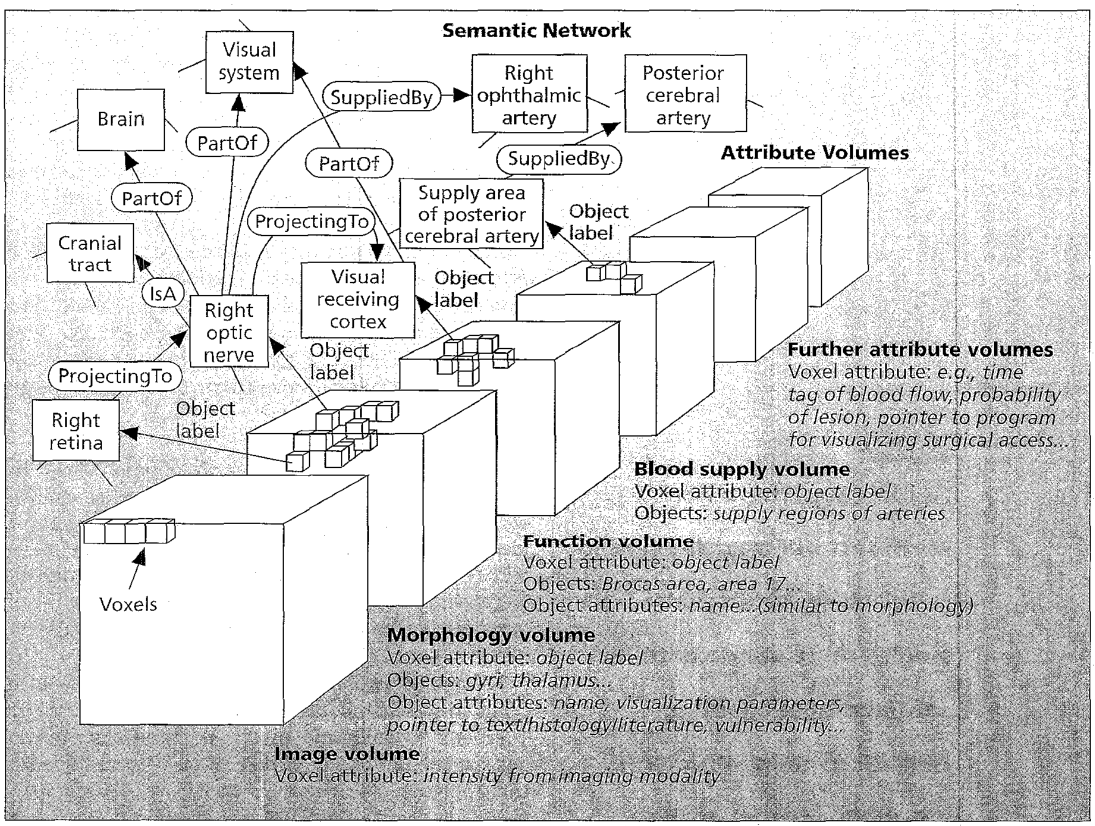

Figure 1. Block diagram of the intelligent-volume data structure consisting of a semantic network linked to a digital volume representation.

sion of links between objects via relations with given semantics. Three groups of relations have been considered so far: one for modeling abstractions, another for modeling structure, and a third for modeling functions. The following examples outline the essentials of the semantic network model.[9]

Figure 1 shows a small section of the network containing some relations concerning the right optical nerve, whose structural relations are modeled via the PartOf relation. Since it is possible to view structures from different points of view (typically the different knowledge domains), the links have the knowledge domains as attributes. Thus, in terms of morphology the right optical nerve is part of the brain, while in functional anatomy it is part of the visual system.

Functional relations such as stimulus propagation may be modeled via the ProjectingTo relation. A stimulus is propagated from the retina through the optic nerve and finally to the visual receiving cortex. The fact that the right optic nerve is supplied by the right ophthalmic artery is described with a SuppliedBy relation. Finally, the abstraction saying that it belongs to the class of cranial tracts is expressed by the IsA relation.

From a model containing these relations, we could ask about the position of anatomical objects in a structural hierarchy, we could ask what structures/areas are involved in stimulus propagation, and beyond that we could inquire about the consequences of a failure of the right ophthalmic artery.

Despite the approach's elegance, we must point out that the vast medical domain is not sufficiently consistent to permit a universally agreed-upon description. Thus, only part of the available knowledge can be represented in the highly structured form of the semantic network linked to a voxel representation. The rest must still be in the form of text and classical pictures, which are nevertheless linked via pointers to the respective objects in the semantic network, as shown in Figure 1. The model's hybrid structure does not exclude unstructured information, but allows continuous conversion of poorly structured data such as plain text into the model's higher structures. Generation of the model is therefore a continuous process driven by practical experience with its application.

Using the tools described above, we are building a semantic network model of the body. So far the model includes 1,000 objects with 2,500 links in the domains of morphology, pathology, functional anatomy, and the vascular system, and it is being refined continuously. It is called the generic knowledge base, since it contains general knowledge that is independent of an actual spatial visual representation or a specific individual (for example, a head acquired with magnetic resonance tomography). For linkage with a visual representation via an actual specimen, the applicable items of the knowledge base are linked to the respective image volume. The resulting data structure is called an intelligent volume. Practical experience has shown that a user easily loses track when the full semantic network is available. Thus, the accessible knowledge may be restricted to what is necessary for an application to a subset, which is called a view.[9]

Glossary of terms

Craniotomy—Surgical opening of the skull.
Endoscope—An instrument for visualizing the interior of a hollow organ.
Gyrus—A convoluted ridge between anatomical grooves.
Histology—The study of plant and animal tissue discernible with a microscope.
Morphology—The study of the form and structure of animals and plants.
Semantic networks—A formalism to describe objects and their relations in terms of nodes and links of a network. Both nodes and links may hold attributes to describe their properties.
Stereotactic—Relating to the technique or apparatus used for directing the tip of a delicate instrument in three dimensions in neurological surgery or research.
Tomography—A method for producing 3D images of the internal structures of a solid object.

FILLING THE MODEL

Figure 2 shows actual generation of the intelligent volume, with atlases of the human brain and skull used as an example. A spatial representation of the brain was obtained by taking an image volume of an individual from magnetic resonance tomography with resolution of 1.5 mm, and the skull was sampled from computed tomogra-

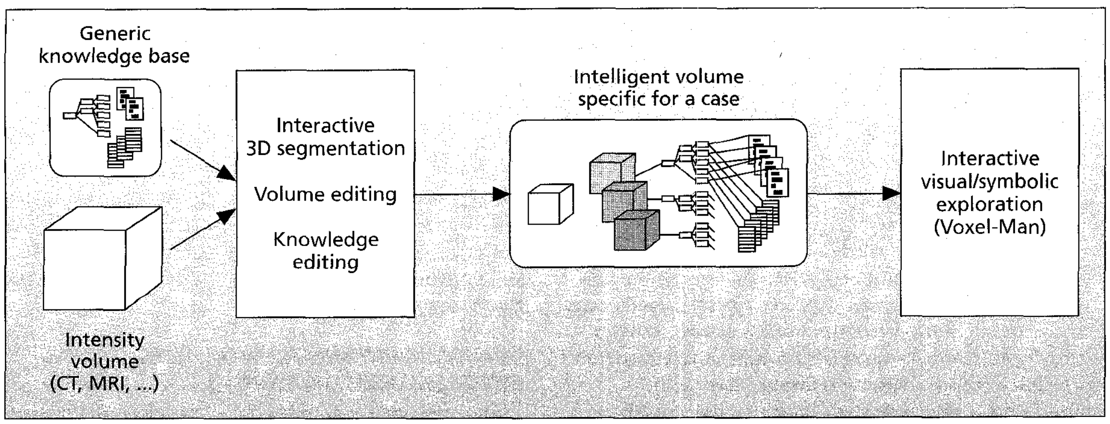

Figure 2. Procedure for generating a virtual body model.

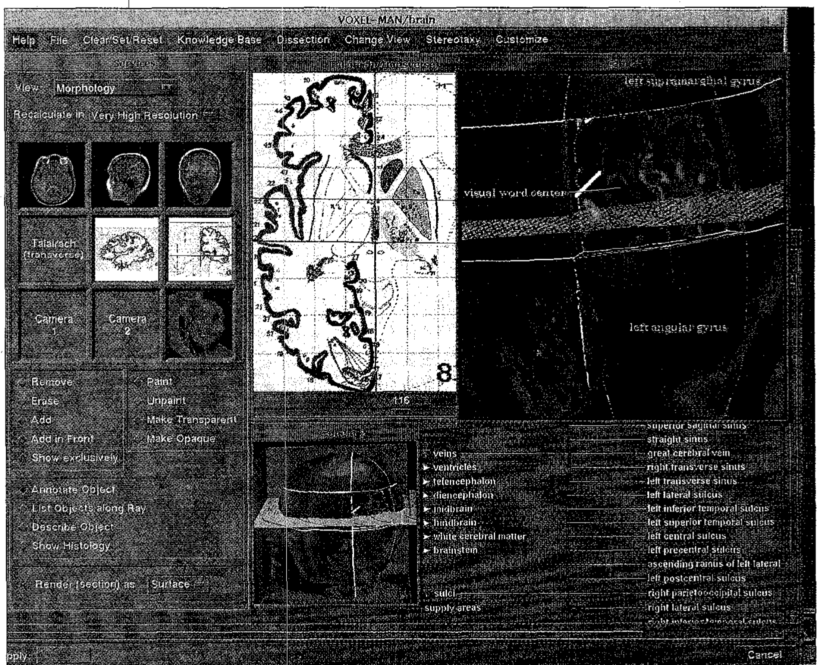

Figure 3. Interactive 3D atlas of the human brain. Left: the menu of exploration functions. Top center: cross section of the Talairach[3] brain atlas. Top right: view of one of the "cameras"; a plane depicts the position of the cross-sectional image. Bottom right: graphical representation of the knowledge base. Objects of interest can be addressed by clicking on the camera image or the symbol in the knowledge base.

phy with an isotropic resolution of 1 mm. The segmentation is done as follows: Initially the gross constituents, such as skull, brain, and ventricular system, are segmented by an interactive segmentation program. A human expert selects the appropriate regions using the intensity window control and special image-processing tools.[10] A volume editor is used to subdivide the coarse components into detailed structural regions (like the gyri). For example, a gyrus would first be identified by painting its extent on the 3D brain surface image. Gray matter (voxels below the painted surface) is identified by specifying an intensity threshold. Refinements can now be made by repeating the painting procedure from different viewing angles and finally painting on the cross-sectional images. Objects such as nerves that are not present in the image data are added via a graphics editor.

Once the spatial extent of an object is defined, the link to the generic knowledge is established by giving the object a name. If, for example, an object has been assigned the name "precentral gyrus," attributes and relations are attached to the object automatically. As one of the consequences, it receives the standard visualization parameters (color, reflectivity, and so forth) of "cortex." Even with advanced editing tools, generating an intelligent volume is tedious. For the atlas of the skull and brain, it took on the order of one man-year to segment the 300 anatomic objects available so far.

However, once the work is done, a knowledge representation is established allowing the user to navigate freely in both the spatial and the descriptive world. For visualizing the spatial world, computer graphics applies simple laws of projective geometry and optics[11] to provide all the effects that a painter would use to paint a 3D scene onto a planar screen. In the resulting system (Figure 3), a viewer can generate arbitrary perspective views by choosing a certain viewpoint, focal length, and light direction of virtual cameras. The pictures appear in windows on the screen.

To explore the model, a user can address an object of interest by clicking on either its spatial representation in the perspective images or a symbol in a textual or graphical representation of the knowledge base (see Figure 3). The system lets the user pictorially add/remove objects, color-mark related objects, and show corresponding histological sections. It also provides information in the form of a textual description or subnets describing relations of the object. The system, which we call Voxel-Man, has been validated in 25 institutions around the world and is now available to the public.[8]

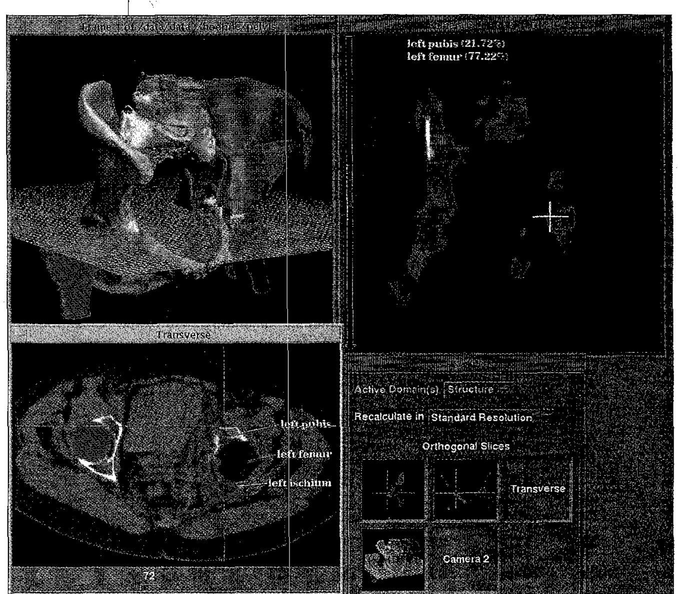

Figure 4. Virtual radiology with the example of an atlas of pelvic fractures. Top left: perspective image of the pelvis with a complicated fracture. Bottom left: computer tomographic picture at the position marked in the perspective image. Top right: simulated X ray from the viewer's position of the perspective image.

NOVEL FEATURES EVOLVING FROM INTELLIGENT VOLUMES

The intelligent-volume approach results in a model represented by a data structure that is primarily independent

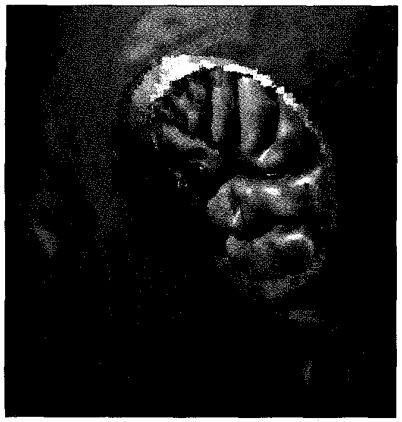

Figure 5. Virtual surgery: The user can rehearse a craniotomy by cutting arbitrarily shaped holes and removing tissue layer by layer.

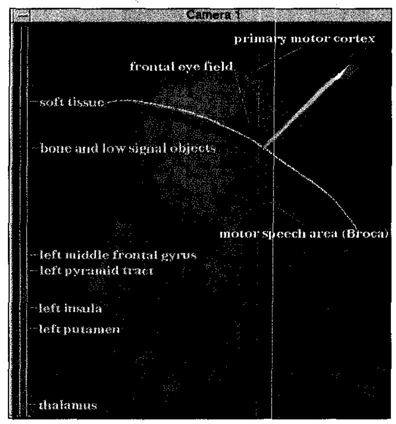

Figure 6. Virtual surgery: simulation of a stereotactic procedure. The objects encountered by the stereotactic probe (arrow) are listed along a "bore hole sample" (left).

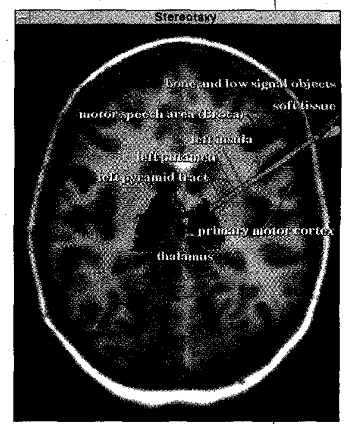

Figure 7. Virtual surgery: alternative display of probe location within an intersecting cross-sectional image.

of an application. We can, however, derive very different applications from it just by providing appropriate exploration tools. Thus, the same model can be used in different ways, as described below.

Virtual anatomy

The most obvious application is simple spatial exploration of the anatomy. In the case of a 3D atlas of the brain, a student could begin to explore the brain model with an outer surface image of the head. The first step could be to simply make cuts across the head and explore the resultant sections. However, an anatomist might prefer to remove the tissue layer by layer. This can be simulated easily by selectively removing objects in the region delineated by the cut planes, as shown in Figure 3. Since the cut surfaces exhibit the texture of the interior, the scene has the appearance of an actual dissection, and of course it can be viewed from any direction.

The crucial advantage of the computer model is that for any visible voxel all related information can be queried. As shown in the figures, the corresponding object names in different domains (such as the name of a gyrus or a cortical region) can be annotated at the cursor position, whether there are sections or surfaces. The corresponding region can be colored as well. The language chosen for the annotations can be English, French, German, Japanese, or Latin. For the brain atlas, text descriptions and sample histological sections corresponding to the objects can be accessed. Information about vulnerability (for example, high for arteries, low for muscles) could be added in the same way.

Questions about the relationships between basic regions can be answered in the same way as they are described in the knowledge base. In the pilot project, for example, the structural "parents" of a basic region (for instance, the lobe to which a gyrus belongs) or functional regions traversed by a stimulus can be queried and colored, displayed, removed, and so forth (see Figure 3). Relations between objects in different domains can in many cases be explored in a simple pictorial way. If, for example, we want to know which cortical regions would be affected by a stenosis, or constriction, in the middle cerebral artery, we would ask the system to mark its supply region on the actual image and then point to the included regions to obtain the color-marked functional regions.

Working in reverse, we can browse through a graphical or textual display of the knowledge base and select an object or group of objects that can be treated as shown above. For example, we could ask for the exclusive display of the thalamus and neighboring objects. While the most elaborate model so far is that of the brain, atlases are also being generated of a fetus, the musculoskeletal system, and the abdomen.

Virtual radiology

Because it is derived from radiological imagery, the model naturally lends itself to teaching and reference in radiological imagery, which precedes any surgical intervention. As shown in Figure 4—a 3D atlas of pelvic fractures—teaching and reference can be done by presenting cross-sectional images in the context of basic three-dimensional anatomy. Furthermore, when the visual model is derived from X-ray computed tomography, 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.

Virtual surgery

With the tools described, surgical operations and stereotactic interventions or punctures can be simulated. Figure 5 shows how a craniotomy can be simulated and the access path to a region of interest explored. Stereotactic surgery can be simulated as well. As Figure 6 shows, objects encountered using a certain position and direction of the probe can be identified automatically. Alternatively, the course of the probe can be assessed on a corresponding cross-sectional image (Figure 7). The locations involved can be expressed in the standard stereotactic coordinate system.[3]

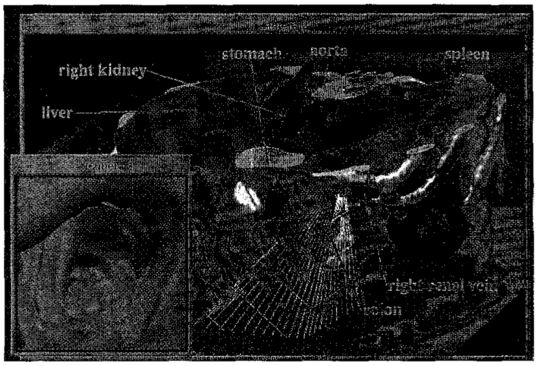

Figure 8. Virtual endoscopy: endoscopic view into the colon (left). The viewer's position is at the top of the pyramid within the patient's abdomen.

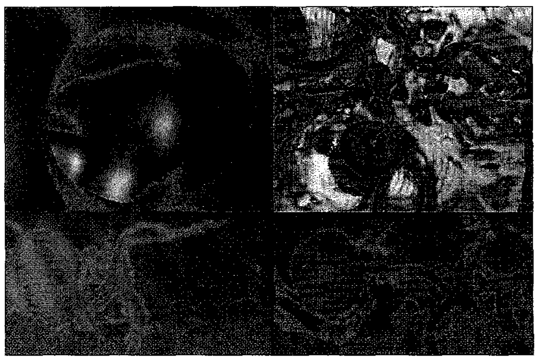

Figure 9. Virtual endoscopy: view from the tip of a catheter along a cerebral artery with an aneurysm (top left). The arrow depicts the viewer's position and viewing direction in three different "scout" views.

Virtual endoscopy

As an added benefit of using computer graphics techniques, the viewpoint can be placed anywhere inside the body. Thus, endoscopic viewing can be simulated and rehearsed. This is especially important because minimal invasive surgery under endoscopic control is an increasingly used technique that requires extensive training. Figure 8 shows the navigation of a viewer within the intestine. Of course, even in this mode, information about the objects encountered can be accessed. This technique works even in small vessels where a real endoscope would not fit. Figure 9 shows the (virtual) view from the tip of a catheter on its way through a cerebral artery to an aneurysm.

Authoring system for other media

In addition to the interactive use, we can of course generate pictures for anatomy or surgery atlases or conventional multimedia systems. Even physical models can be created, for example, with the technique of computer-controlled stereolithography. Or we can program scripts that generate movies showing a surgical procedure or the animation of the blood flow, for example. A novel feature is that we do not have to edit the material again if the underlying knowledge changes. The same scripts (possibly with some modifications) would produce the new material automatically.

Other uses

We believe that these applications of the intelligent-volume approach represent only a portion of what is possible. Other physicians or researchers may have quite different ideas on how to use the knowledge represented in this form—perhaps as a pictorial dictionary or simply as a spatial index for literature search. In the latter case, one exotic application could be to color-code the number showing how many publications are related to any part of the cerebral cortex.

THE INTELLIGENT-VOLUME APPROACH lets us derive all the traditional aids for visualizing anatomical and functional knowledge (cadaver dissection, pictures, classical atlases, movies) and to generate new simulation capabilities not previously possible (simulation of surgery and medical imaging). Such flexibility, of course, entails extensive hardware requirements. A Unix workstation with at least 96 megabytes of main memory is needed for achieving satisfactory speed (seconds for medium-resolution interactive work and minutes for high-quality rendering of large images). However, high-end PCs under Linux, with the same amount of memory, achieve similar performance.

While the general concept of this approach has proven valid and its practical usefulness in special applications has been demonstrated, a really general model of the human body with all simulation capabilities is still a long way off. More powerful computers are needed so that the spatial resolution can be increased substantially by using higher resolution imaging, including histological cross-sectional imaging.[7] We have taken a first step toward this goal by using the Visible Human data.[12] However, a full-resolution model would exceed the current storage capabilities of today's general-purpose computers. Moreover, at this time the model is static, although it may be possible to include a biomechanical model for simulation of motion and deformation (to animate joints or heart motion or to feel mechanical properties using a virtual reality environment). Finite-element techniques are available for this purpose, but they are still too complex to run interactively on an affordable computer.

Problems arising in general modeling are more severe. If we want to map standard textbook knowledge into a formal representation, we encounter inconsistencies arising either from historical development or from different views of the same situation. Even though we developed a general solution for this problem,[9] the limits of semantic network modeling for our purpose are unclear. A further problem is the description of variations related to age or individual differences. Knowledge in anatomy is certainly "fuzzy" (consider, for example, the boundaries of functional cortical areas or the extent of a tumor). Thus, solutions to presenting such knowledge can be expected to vary.

Although the present model is far from general, its versatility already offers a virtually infinite number of ways to use it. We are surprised at the different paths users find to navigate through both knowledge and pictorial space, and they often generate types of pictures and procedures that we had not thought of. We are convinced that models like Voxel-Man will constitute the medical knowledge representations of the future. ■

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