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Virtual Reality Applied to Hepatic Surgery Simulation: The Next Revolution

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Objective
This article describes a preliminary work on virtual reality applied to liver surgery and discusses the repercussions of assisted surgical strategy and surgical simulation on tomorrow's surgery.

Summary Background Data
Liver surgery is considered difficult because of the complexity and variability of the organ. Common generic tools for presurgical medical image visualization do not fulfill the requirements for the liver, restricting comprehension of a patient's specific liver anatomy.

Methods
Using data from the National Library of Medicine, a realistic three-dimensional image was created, including the envelope and the four internal arborescences. A computer interface was developed to manipulate the organ and to define surgical resection planes according to internal anatomy. The first step of surgical simulation was implemented, providing the organ with real-time deformation computation.

Results
The three-dimensional anatomy of the liver could be clearly visualized. The virtual organ could be manipulated and a resection defined depending on the anatomic relations between the arborescences, the tumor, and the external envelope. The resulting parts could also be visualized and manipulated. The simulation allowed the deformation of a liver model in real time by means of a realistic laparoscopic tool.

Conclusions
Three-dimensional visualization of the organ in relation to the pathology is of great help to appreciate the complex anatomy of the liver. Using virtual reality concepts (navigation, interaction, and immersion), surgical planning, training, and teaching for this complex surgical procedure may be possible. The ability to practice a given gesture repeatedly will revolutionize surgical training, and the combination of surgical planning and simulation will improve the efficiency of intervention, leading to optimal care delivery.

Surgical simulation increasingly appears to be an essential aspect of tomorrow's surgery. A hepatic surgery simulator involves virtual reality, an advanced concept that will transform the medical world. By means of computer science and robotics, virtual reality extends the perceptions of our five senses by representing more than the real state of things. It involves three concepts: immersion, navigation, and interaction.

Immersion can be mental, in that the operator immerses himself or herself in the image by thought; this is what happens when we look at a three-dimensional (3D) image on a screen. Immersion can also be physical, calling for sophisticated techniques such as stereoscopic headgear and datagloves that give the impression of having passed though the mirror of the screen. *Navigation* is the ability to move and to meet in the virtual universe that modern telecommunications networks are about to create. *Interaction* is the ability to interact with the image in real time, to manipulate and to transform it just as if it were material.

There are three reasons why we developed a hepatic surgery simulator. The first is to provide the surgeon with a comprehensive visualization of the organ, allowing accurate presurgical localization of the pathology and perception of

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its relations with vascular and biliary ducts. This allows the surgeon to plan the best surgical approach. The second reason is to allow planning and realistic surgical simulation, much like the detailed flight plans used by commercial jet pilots. The surgeon will be able to perform the procedure virtually and thus will be better prepared for the intervention through immersion in the surgical conditions. The ability to practice a given gesture or procedure repeatedly will have a great impact on surgical training and education and will diminish the need for live animal surgical training. Physiologic simulators will make it possible to predict the patient's postsurgical course, depending on the intervention.

The third reason is that virtual reality is an integral part of computer-assisted surgical procedures. Augmented reality will superimpose the virtual image—that is, the organ (including arborescences and tumors) and the preplanned strategy—onto the real operating view. This will streamline the procedure because the surgeon will have precise knowledge about the position of crucial elements that were formerly unseen. Transmission of all this information—virtual and real images—will allow the surgeon to discuss the case with experts both before and during surgery; thus, the strategy can be revised as needed.

A sophisticated simulator must meet five requirements: visual fidelity, interactivity, physical properties, physiologic properties, and sensory input and output.[1] In this report, we describe how to produce a realistic 3D model of the liver from bidimensional (2D) medical images for anatomic and surgical training. The introduction of a tumor and the consequent planning and virtual resection are also described. We address the problems of physical modeling and force feedback and how they relate to the realism of 3D representation for immersion and navigation, and real-time interaction.

MATERIALS AND METHODS

Materials

A processing workstation (DEC 500/333, ZLXPL2 graphics card, 512 megabytes of random access memory) was used to process images and reconstruct models. Visualization was done using two different graphics workstations (Telmat TWS 88, two graphics cards, and SGI Octane SI). Deformations require a Laparoscopic Impulse Engine (Immersion Corp., San Jose, CA) connected to a personal computer running Linux (Pentium 166, 64 megabytes of random access memory).

We used the image processing libraries developed by the Epidaure group from the Institut National de Recherche en Informatique et Automatique. The first control steps of visualization were done using the Application Visualization System (Advanced Visual Systems, Waltham, MA). More specific requirements (for both image processing and visualization) were fulfilled by developments of our own, using C, Motif 1.2, and OpenGL.

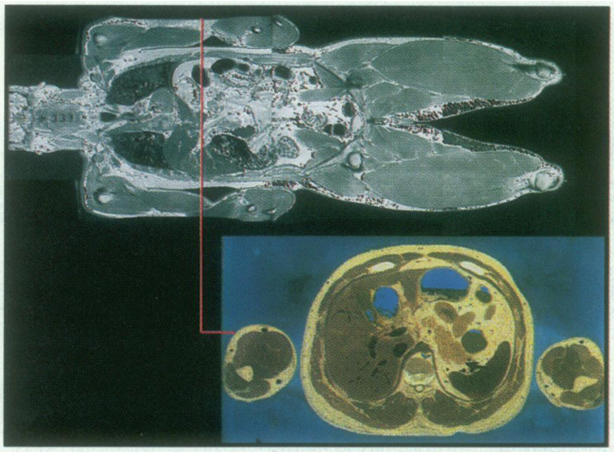

Figure 1. Sample images of the National Library of Medicine data set. (Top) Juxtaposition of longitudinal T2-weighted MRI. (Bottom) An axial photographic image.

We used the set of sliced image data from the Visible Human Project (Fig. 1), collected by the National Library of Medicine (NLM, Bethesda, MD).[2] There were 1871 cross-sections for anatomy mode obtained from a male cadaver. The axial photographic images are 2048 × 1216 pixels, where each pixel is 0.33 × 0.33 mm wide and is defined by 24 bits of color. The size of each image is 7.125 megabytes. The anatomic cross-sections are at 1-mm intervals; those used for building the 3D liver model represent 183 slices. The images were downloaded from the Internet after a licensing agreement had been signed with the NLM.

Methods

To create a realistic model of the liver, we used a set of techniques for medical image analysis.[3] The reconstruction task was broken down into two steps: extraction of the external shape of the liver, and extraction of the four internal arborescences (Fig. 2).

The goal of the first procedure was to detect the contours of the liver in 38 slices. It consisted of a semiautomatic 2D contour extraction of the liver parenchyma every 5 mm. We used semiautomatic deformable models (snakes)[4] after contrast enhancement, application of a Sobel filter for contour detection, and rough initialization. The shapes (38 slices) thus generated were piled up to build a 3D voxel model (Fig. 3). The modeling step converted the 3D voxel image into an image based on geometric information, with polygons as basic primitives. To obtain a smooth, light, and easily manageable model, a mesh was constructed from the voxel image. 3D active meshes (Simplex mesh)[5,6] were used to obtain the geometric representation (see Fig. 2). Different representations of the liver model are possible: the anatomic model is very accurate (14,000 triangles), but it can be simplified for various reasons, such as more fluid visualization, or simulation.

The second procedure involved the detection and extrac-

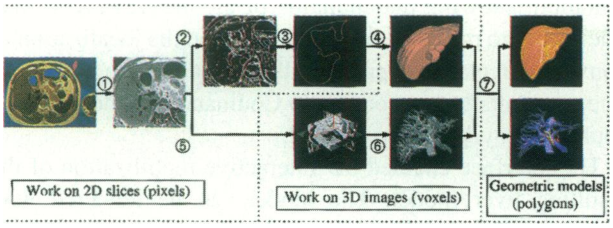

Figure 2. Steps in image reconstruction. 1. Area selection and conversion to gray levels. 2. Preparation of the image for snake computation: Sobel contour filtering and thresholding. 3. Detection of the contour of the liver by snake computation. 4. Piling up the surfaces defined by the snakes in a three-dimensional voxel image. 5. Three-dimensional voxel image homogenization. 6. Extraction of the arborescences through hysteresis filtering, connected components extraction, and manual intervention. 7. Geometric modeling.

tion of the vascular and biliary ducts in the photographic images. The work was restricted to the red component because a paste inserted into the man's body interfered with the blue and green components in the images. We simultaneously treated all the 2D slices, implying the use of 3D image processing steps. The data set (183 slices) presented two variations in intensity: the mean intensity varied from slice to slice, and the liver tissues were not homogeneous, so a first-order variation, along the y axis, was denoted. The intensity of the parenchyma then had to be homogenized. A bilinear approximation using the Monte Carlo method (based on hazard) and correction produced a 3D image with an homogeneous liver area, on which intensity-based treatments could easily be applied (Fig. 4). We used hysteresis thresholding to select the areas in the volume that had intensity similar to the arborescences. A connected components extraction (3D propagation algorithm, tracking neighboring voxels of similar intensity) then was used to separate the various areas thus found, and we selected the ones that were arborescences. Morphologic image processing tools cut the possible interconnections between arborescences (see Fig. 4). The hepatic artery, barely visible to the naked eye, had to be drawn by hand by marking points on the 2D slices. The conversion from the voxel representation to a geometric mesh was identical to the former description of the organ's envelope.

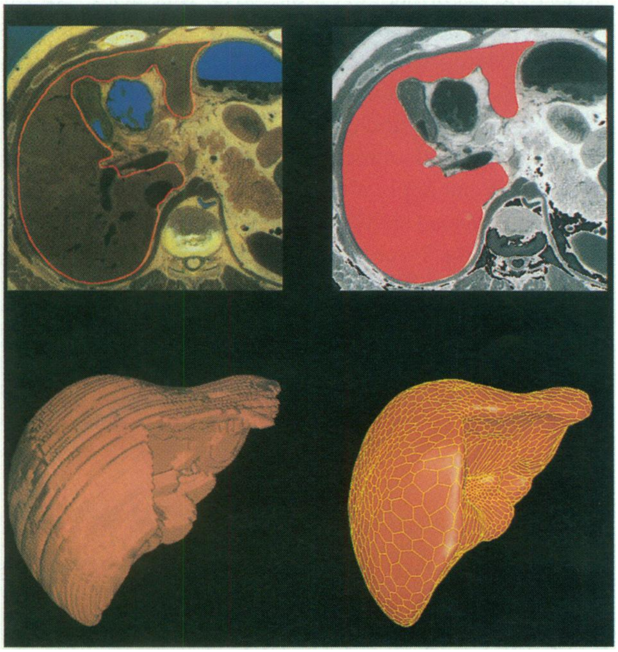

Figure 3. Envelope reconstruction. (Top left) Part of a photographic cut containing the liver. The red contour shows the result of a snake computation. The contour thus extracted is then converted to a slice (top right), and the slices obtained in the different cuts are piled up (bottom left). (Bottom right) Result of the application of a mesh on the former image.

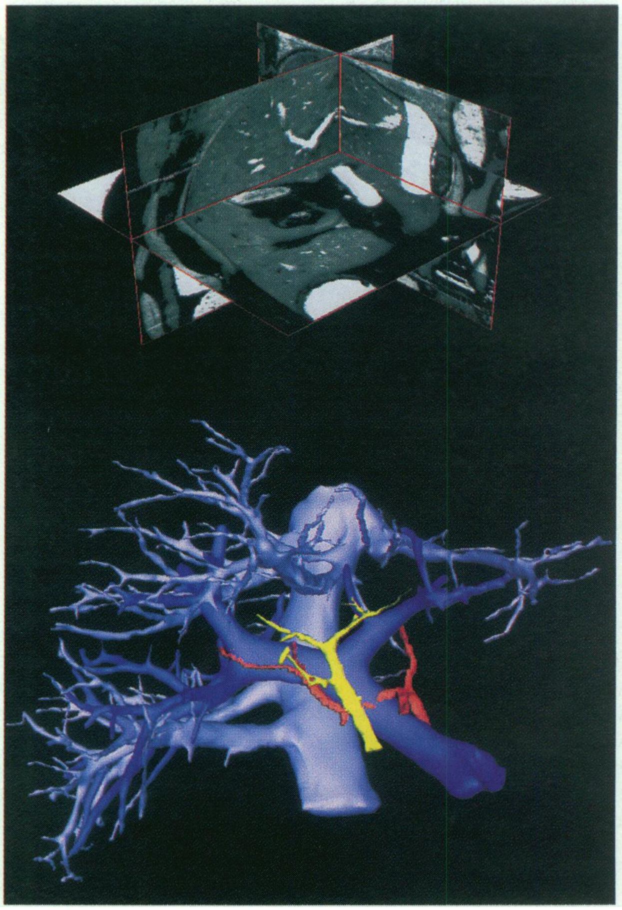

Figure 4. Initial and final reconstruction steps for the arborescences. (Top) The Visible Man's set of cuts, piled in a three-dimensional image, on which histogram manipulations have helped to enhance the perception of the arborescences (in white). (Bottom) The arborescences extracted after they have been converted in a geometric mesh.

An interface was developed to visualize the extracted results. Artificial spherical tumors were manually placed in the liver volume. The security margin was represented by a volume with a radius 1 cm bigger than the tumor. Texture mapping was implemented; the textures were extracted from photographs taken during laparoscopic interventions and converted into a texture plane (Fig. 5)[7].

The deformations of the organ model were subject to linear elasticity and were solved using a finite elements method. The

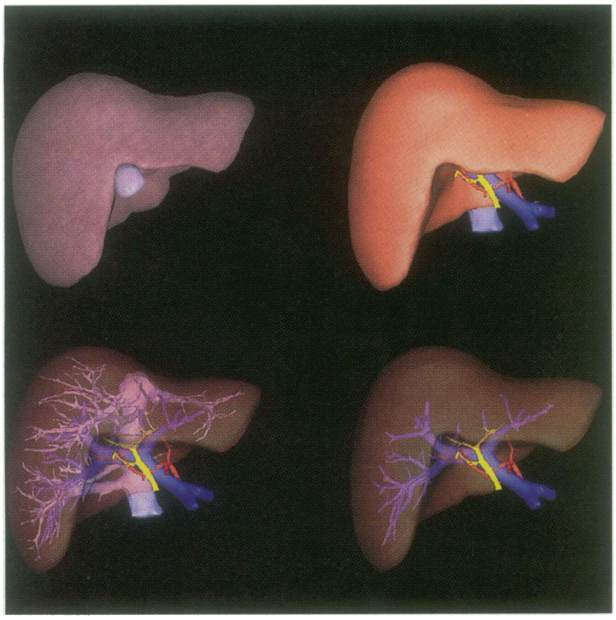

Figure 5. Various possibilities offered by surface rendering. The textured image (top left) is a realistic one. However, anatomic perception is easier with nontextured rendering (the other three figures). Opacity variation is illustrated by the change between the top right and bottom left images, where the internal arborescences can be seen through the transparent envelope. Object management is illustrated in the bottom right image: by removing the vena cava and the hepatic veins from the scene, the user can have a clear perception of the anatomy of the portal vessels.

volume of the liver was broken down into a set of tetrahedrons (Fig. 6). A superposition principle was used, allowing us to obtain displacement at each point of the solid by separately applying each force, and then adding their various effects. A preprocessing step was used to evaluate the influence of the displacement of any node on any other node.[8]

The force feedback system we use provides five degrees of freedom, three controlled by force. The accuracy for displacement measurements was about 25 μm, and the maximal force that could be exerted along the trocar axis was 8.9 Newtons. A personal computer controlled the robotic device (position acquisition and force application) as well as collision detection. The graphics workstation calculated the deformations, displayed the liver and virtual tools, and sent the value of the reaction force to the computer. Both stations exchanged information through an Ethernet link, using User Datagram Protocol.

RESULTS

The first result was a 3D reconstruction of the liver that could be visualized interactively from any viewpoint. It consisted of both the external shape of the liver (3900-triangle surface), which included detailed elements of the liver shape (hepatic hilum, gallbladder bed), and the arborescences (vena cava and hepatic veins 27,800 triangles, portal vein 10,100 triangles, hepatic artery 4500 triangles, biliary tree 1600 triangles). It had a smooth optimal representation, allowing manipulation of the model in real time. The ability to rotate those models enabled the localization of nonvascular planes separating the eight hepatic segments. The segmentation, according to Couinaud's nomenclature,[9] could thereby be easily defined.

The interface enabled 3D interactive mobilization of the resulting liver model. The model can be rendered with texture application (Fig. 6) or without. The attributes of any graphic object (color, transparency, shading) can be modified to provide the user with a more comprehensive view of the organ. Clipping of a surface mesh was implemented; this allows the surgeon to place resection planes and to realize a virtual resection depending on the location of the tumor. The illustration of a right hepatectomy is shown in Figure 7. The current implementation enables positioning of three points. This method gave a virtual segmentation close to the anatomic definition because it was based on landmark points (scissure, recessus, and vascular branch extremity). Once the plane was defined, the trace of its intersection with the objects in the scene was shown, and it was still possible to adjust it. The liver was virtually cut and two (or more) elements were thus delimited and separated. The cut vascular and biliary ducts appeared on the separation surface. This resection was a preliminary step for the simulation of a surgical procedure. It would then be possible to define an ideal resection according to the spatial positioning of a hepatic lesion and to Couinaud's segmentation. Computing the resultant volumes of the hepatic elements so obtained gave an initial approximation of the residual hepatic function.

Real-time deformation of the liver was achieved with force feedback calculations simulating hepatic tissue resistance. The deformation had an effect on the volume—in other words, pressure on one side of an object influenced all the interior elements and consequently the opposite side. An initial sophisticated immersion involved a force feedback device: users can apply a force on the external shape using a robotic interface (including a laparoscopic surgical tool), and the real-time force feedback computation will enable them to feel the resistance of the hepatic tissue through the mechanical system (Fig. 8).

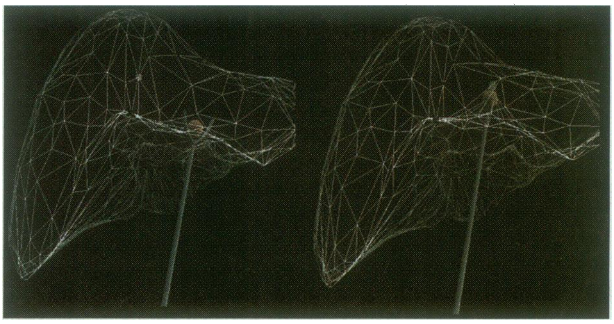

Figure 6. Deformation of a mesh. (Right) A push on the mesh, with the contact point materialized by the red sphere. The repercussion on the upper face of the liver, produced by computing the deformation on the volume, can be seen through comparison with the mesh at rest (left).

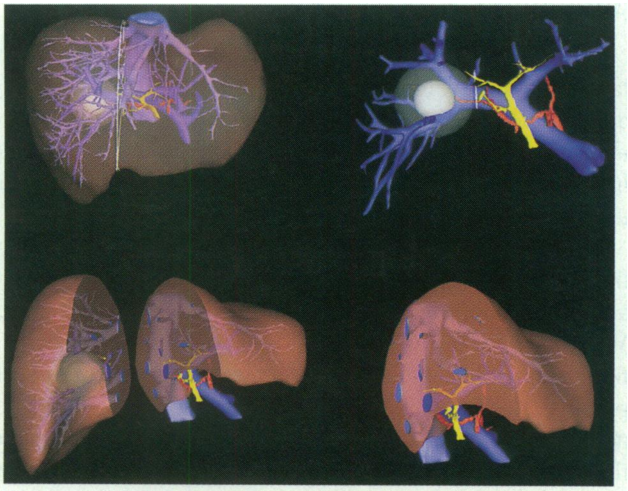

Figure 7. Virtual right hepatectomy. Based on the organ's anatomy and the tumor location, a resection plane is defined (top left). The arborescences and the position of the plane with respect to the margin around the tumor can then be controlled (top right). After the resection is computed (bottom left), the result is visualized and validated (bottom right).

The preprocessing computations, which are essential for reducing real-time calculations, can last a few minutes to several hours, depending on the size of the model and the accuracy desired.

DISCUSSION

Our aim was to expand the use of computer science in various fields of medicine. Virtual reality will revolutionize the teaching of anatomy and surgery. The most spectacular aspect, surgical simulation, is no longer just a concept, as witnessed by the research carried out by other groups.[10–20] Few people, however, have been working on including interactions with deformable organs.[21–23] Our work includes applying virtual reality concepts to all the steps involved in surgery, from presurgical planning using patient data analysis and visualization to surgical simulation using real patient data.

3D Visualization

Virtual reality images differ from the elaborate synthesized images that require hours of computation before they can be visualized and assembled into film. On the contrary, virtual reality requires an image computed in real time and is influenced by highly unpredictable user actions. The image is interactive; precomputed images are not.

3D visualization of the organ is the first step of a virtual immersion. Two types of visualization are most often used: volume rendering and surface rendering.[24,25] The first, based on voxels (visual rendering based on volume elements, or volume rendering), requires few or no segmentation stages (computer detection of the various entities represented in the image). Volume rendering today allows the interactive visualization of only small volumes on standard workstations because of the amount of resources required (memory and processing).[26,27] The image perceived is close to the original scanner image. The analysis—in other words, the determination of the limits between objects—is completed by the human eye.

The second method for visualization, involving geometric models (based on a mesh molding of the surfaces, or surface rendering), requires precise computer image segmentation before visualization. Nevertheless, this surface rendering offers a faster 3D handling (quick mobilization of the object in space) and higher interactivity. The visual perception/readability of the virtual organ is thereby enhanced because the objects to be visualized are precisely delimited.

Visualization for the diagnostic step, tolerating a fairly low refresh rate (up to about five images per second), can be based on either of these two methods. Volume rendering is becoming more accessible; we expect it to become one of the main visualization methods for medical data. Concerning the simulation, however, the object's structure must be

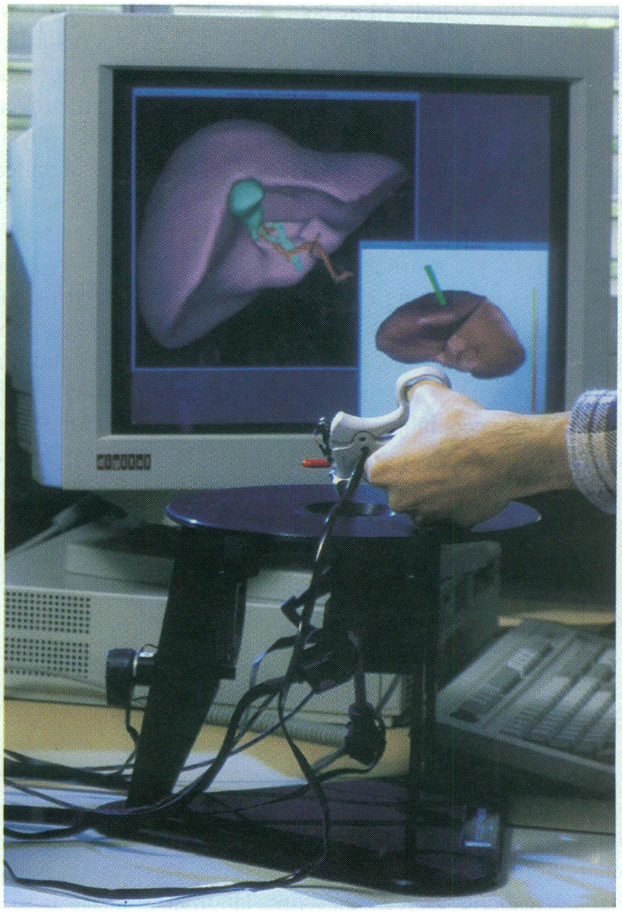

Figure 8. Interaction system. In the foreground, a user moves the handle of the Laparoscopic Impulse Engine. The background computed image shows, in the lower right corner, the consequent deformation on the liver model.

able to be modified by giving it behavioral properties. Up to now, this has been possible only with geometric representation.

Geometric models are nevertheless subject to certain constraints. A realistic simulation requires high refresh rates of 50 images per second for the display and 1000 updates per second for the feedback force. The lower the number of polygons to be displayed, the quicker the display and the better the interactivity. It is therefore important to optimize the number and the shape of the polygons that define the object.

The 3D effect, rendered by color adaptation according to the light incidence on each polygon, depends on the quality of the graphics card used. Until recently such cards were available only on sophisticated workstations, but they are now becoming increasingly common on desktop computers.

The interactive management capabilities are numerous: position, color, perspective, transparency, and fogging all help to offer greater perception of the 3D image.

Reconstruction

An essential step before working on patient data was based on the Visible Man data set. The model semiautomatically obtained serves as a reference on which further developments can be based. It was also the first support for exchanges between scientists and physicians, and proved efficient at matching technical possibilities against physicians' expectations. This model was also the first detailed reconstruction of the organ and is, to our knowledge, the most precise one in terms of diagnostic and planning tasks.

The liver reconstruction from the NLM photographic images was done using classic image processing algorithms (deformable models, histogram manipulation, and morphologic tools). In fact, the unique nature of this work did not warrant specific research for algorithms, and manual intervention was acceptable at some key points (extraction of the hepatic artery, for example). The initial 3D modeling of the arborescences, represented by too great a number of polygons, had to be simplified. The properties associated with Simplex meshes enabled the polygons to be concentrated in the areas of higher curvature. This results in a mesh presenting an optimized ratio of polygons to precision.

Strategy Planning

The interactive placement of objects in a 3D environment to be perceived through a 2D projection on a screen is a tedious task. We therefore resorted to a method exploiting anatomic information. Selecting three consecutive points that correspond to real anatomic landmarks is close to a surgical approach. Once the plane has been defined, its interaction with the arborescences can then be visualized and its position modified.

Interaction

Organs in the human body have complex deformation laws. Different solutions have been proposed for modeling deformable objects, both in the computer science and biomechanical fields.[28–30] We chose a simple model offering interesting properties for quick deformation and computations of reaction forces.

The main constraint for model deformations is real time; this implies a graphics refresh rate of 25 images per second, and at least 500 updates of the force feedback per second. We resorted to linear elastic deformations computed using a finite elements method. Such elements are tetrahedrons and produce a computation of the deformations on the volume, not only the surface. This enables the volumetric distribution of the parenchyma to be taken into account. The deformation parameters for each of the elements are related to their anatomic correspondence in the original computed tomography scan image. Finite elements computations are usually too complex for a real-time application. We introduced a preprocessing step to reduce the computations needed during simulation. This allows realistic deformations to be present on a precise model—that is, a model with a large number of nodes and triangles. The system will have to be completed and modified by an on-going rheologic study; this will provide us with exact deformation parameters based on the real deformations of liver parenchyma. Implementation will thereafter have to respect the two main constraints: real time and accuracy of deformation.

The interface with the machine must be similar to a real surgical intervention. The deformations are currently associated with a single force feedback system, but this will have to incorporate other instruments as well as a camera. The other organs of the abdominal cavity will also have to be included.

Perspectives

This ongoing study is of interest only in terms of its adaptation to patient data. This adaptation involves medical image analysis (computed tomography, magnetic resonance imaging) to extract the necessary structures (the envelope and venous arborescences, at a minimum). We have begun the analysis of a scanner image to obtain a model that is the exact representation of a patient's liver. The 3D presurgical visualization will provide the surgeon with in-depth knowledge of the topographic anatomy and the precise localization of pathology in the liver. The extraction quality depends on both the images and the algorithms. We no longer should have to draw the contours of the liver, arborescences, and tumors by hand, as was done in preliminary studies.[31,32] The extraction is expected to evolve because of improvements in image and processing algorithms: a semiautomatic process will thus become automatic. This will save time (removing the need for tedious manual segmentation), will make the system easier to use (obviating the need for adjusting processing parameters properly), and will permit an objective, reproducible, and operator-independent reconstruction. The automated reconstruction steps will have to be studied before use until their robustness has been proven through clinical validation.

The first automatic extraction algorithms have begun to appear.[33,34] The integration of specific patient data (medical file, 3D visualization, and physiologic simulation) with information from bibliographies or former case studies or from off-site experts (by means of teletransmissions) will lead to optimal care delivery.

A 3D representation of the organ on which various anatomic information can easily be visualized will enable the surgeon to anticipate the results of actions to be taken during the procedure. Various scenarios and gesture-related difficulties can be evaluated using realistic simulation. Repetition of a virtual operation will become a key point in the surgeon's training. Training on simulators will allow neophyte surgeons to practice until they master the technique, eliminating many of the ethical problems associated with live animal training. A parallel evaluation system will give an objective measurement of a surgeon's progress and will enable person-specific teaching.[35]

To be effective, simulation must be as realistic as possible: the immersion is perfect when it is no longer possible to distinguish simulation from reality. The technical constraints of such a simulator make its realization difficult.[36]

One of the first steps in using a simulator is to acquire precise skills: for example, eye–hand coordination with visualization of the surgical field through a screen, such as every surgeon had to do in his or her initial attempts at laparoscopic surgery. In this case, the quality of the visual feedback and the surgical environment is less important, but the tactile perception, on which the training is based, must be realistic. This involves a high rate of visual and force feedback.[37]

Finally, the idea of using a simulator in gastrointestinal surgery has arisen from the laparoscopic approach, this in itself due to a televisual approach, which is also the interface of virtual reality. Further, this particular approach implies a therapeutic gesture by the means of instruments introduced through fixed points on the abdominal wall, allowing easier modelization of their moves and actions to be envisioned. The knowledge of the anatomy and the surgical strategy for each patient leads us to foresee laparoscopic operations on the liver, with the possible help of robotics tools or augmented reality.[12,38] If biomechanical influences in orthopedic surgery have to be known, physiologic repercussions will have to be determined before undertaking a hepatic resection. By merging realistic simulation and the simulated outcomes of surgery, the surgeon will not only be able to plan an operative strategy, but also to have it validated by a second expert and experiment with alternative surgical procedures and repeat the most efficient one, taking into account the physiologic impact during and after the procedure.[39]

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