Surgical Simulation Using Virtual Reality Technology: Design, Implementation, and Implications

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A tremendous demand exists for enhancing the way by which physicians learn new invasive procedures. Appropriate education in new medical and surgical procedures is often outpaced by the desire of physicians to incorporate a procedure in their practice. Computerized surgical simulations have the potential for improving surgical morbidy and mortality. Studies have shown that, for a wide range of diagnostic and therapeutic procedures, doctors doing their first few to several dozen cases are much more likely to make a greater number of errors.[1] This phenomenon has been referred to as 'the learning curve.'[2] Adequate proctoring of learners by experienced surgeons is cumbersome, as there are few surgeons experienced to proctor their colleagues. It is difficult for physicians, particularly those in rural areas, to travel to larger medical centers for training. The requirement also places a burden on experts who could become overwhelmed with proctoring requests, in addition to leaving their clinical responsibilities.

Virtual reality (VR) technologies are increasingly becoming more applicable in medicine for a variety of reasons. The high cost of traditional training resources stems in part from the use of laboratory animals and the need for physician proctors. Furthermore, the availability of training opportunities for surgeons and residents is determined on a case-by-case basis. VR systems allow for laparoscopic training opportunities at any time. VR simulation systems not only decrease training costs, they also make possible the reduction of operative risk associated with new technologies in medicine. Significant operative risk reduction could be made possible by the development of a simulator which allows transference of skills from the simulation to the actual patient contact. Several studies have supported the credibility of computer based simulations; as users have reported that these simulations accurately represent clinical encounters with patients.[3,4,5]

This paper covers the technical issues involved in the creation of surgical simulation software. It also documents surgical simulation software developed and shown during the 1994 American Urologic Association and The American College of Cardiology meetings. Through an understanding of the technical considerations of surgical simulation, the surgical community can better appreciate the challenges involved in this educational simulation - its limitations as well as potential for changing the process of surgical education and credentialing.

Current Computer Hardware Technology

Although there is a definite need for surgical simulations, the implementation of this technology involves many challenges. The first challenge is to determine computational needs of system. The requirement of real-time surgical simulation requires a programmable system with extensive three-dimensional rendering capabilities. Furthermore, the system has to be programmable and allow an upgrade path. IBM compatible Pentium PCs and Macintosh Quadra and PowerPCs do not have adequate three dimensional rendering capabilities. Today's personal computers lack the requisite polygon per second 3D rendering speed that is required. Although game machines including Atari's Jaguar system, 3DO, and other systems are often faster on a polygon per second measure than personal computers, they are still not adequate for real-time physically-based virtual organ rendering.

One practical computer hardware solution to the challenges involved in surgical simulation are workstations produced by Silicon Graphics, Inc (SGI). SGI machines provide the highest polygon per second rates and can be programmed using standard computer languages such as 'C' and 'C++.' In addition, the SGI machines are binary-compatible across their product line, insuring that software written for their lowest-end machines also will run on their graphic supercomputers.

Extensive 'virtual reality' authoring packages or 'tool kits' have been designed and marketed, but none of these packages allow for the construction of virtual worlds in which objects can be flexed, cut, and compressed in real-time. In addition, no commercial packages simulate bleeding.

Creating Virtual Organs

HT's **TELEOS**™ software environment utilizes several computational techniques which allow the display of models with extensive detail, while maintaining real-time frame rates. Central to **TELEOS**, is the use of spline-based modeling. Anatomic modeling using splines affords several advantages: ease in modeling anatomic movement, ability to offer changes in level of detail. With variable cross-sectional detail, along with the number of cross-sections which occur along a given spline, anatomic detail can be continuously varied to insure both optimal anatomic detail and real-time frame rates.

Diagram 1 provides a flow-chart of how **TELEOS** creates a 'virtual organ' from standard medical imaging systems (CT, MR, or others):

1. Registration & Segmentation

The first processing **TELEOS** facilitates the registration and segmentation of sequential two-dimensional (2D) data from medical imaging systems. Magnetic Resonance (MR), Computer Tomographic (CT), and other imaging systems can be used to create series of individual medical images. To reconstruct these 2D images into a basic three-dimensional (3D) object, the 2D images must be accurately stacked and aligned. Simultaneous to image registration, the tissue boundaries can be segmented to create outlines of the cross sections of each organ.

2. Geometric Polygonal Surface Reconstruction

Once outlines (vectors) of all the cross sections of different tissues are available, the database is reconstructed in three dimensions as a geometric (polygonal) surface model. This is achieved by connecting corresponding points along the outline of sequential cross-sections constituting surface patches of polygonal meshes.

3. Physically-based Polygonal Reconstruction

Useful interaction with virtual tissues demands the encoding of realistic behavior into the tissue's formal description. In a physically-based approach, such a behavior is intrinsic. The definition of the model extends to include physical parameters. Models thus created can behave in accordance with classical dynamics and Newton's laws of motion.

To convert our geometric database into a physically-based one, TELEOS simulates the behavior of tissues as flexible bodies based on mass elements and springs. An ordinary polygon is represented by vertices and edges. The vertices in a physically-based polygon are additionally qualified by mass, velocity and acceleration vectors and edges are represented as springs with linear or exponential behavior, stiffness and damping constants. Tissue characteristics can be configured by editing the physical parameters of the involved springs and mass points.

Implementation of Software for Virtual Reality Surgical Training Simulator

Ultimately, a successful surgical simulator facilitates skills transference to actual patient contact during procedures. To insure the educational utility of the software, we have focused on the areas in which surgeons encounter the most difficulty.

We aim to improve on motor skills, anatomic recognition and orientation, and performance of surgery. In order to achieve these goals, the following technical specifications must be met:

- Maintenance of real-time frame rates (greater than 15 frames per second) for simulation using software techniques.

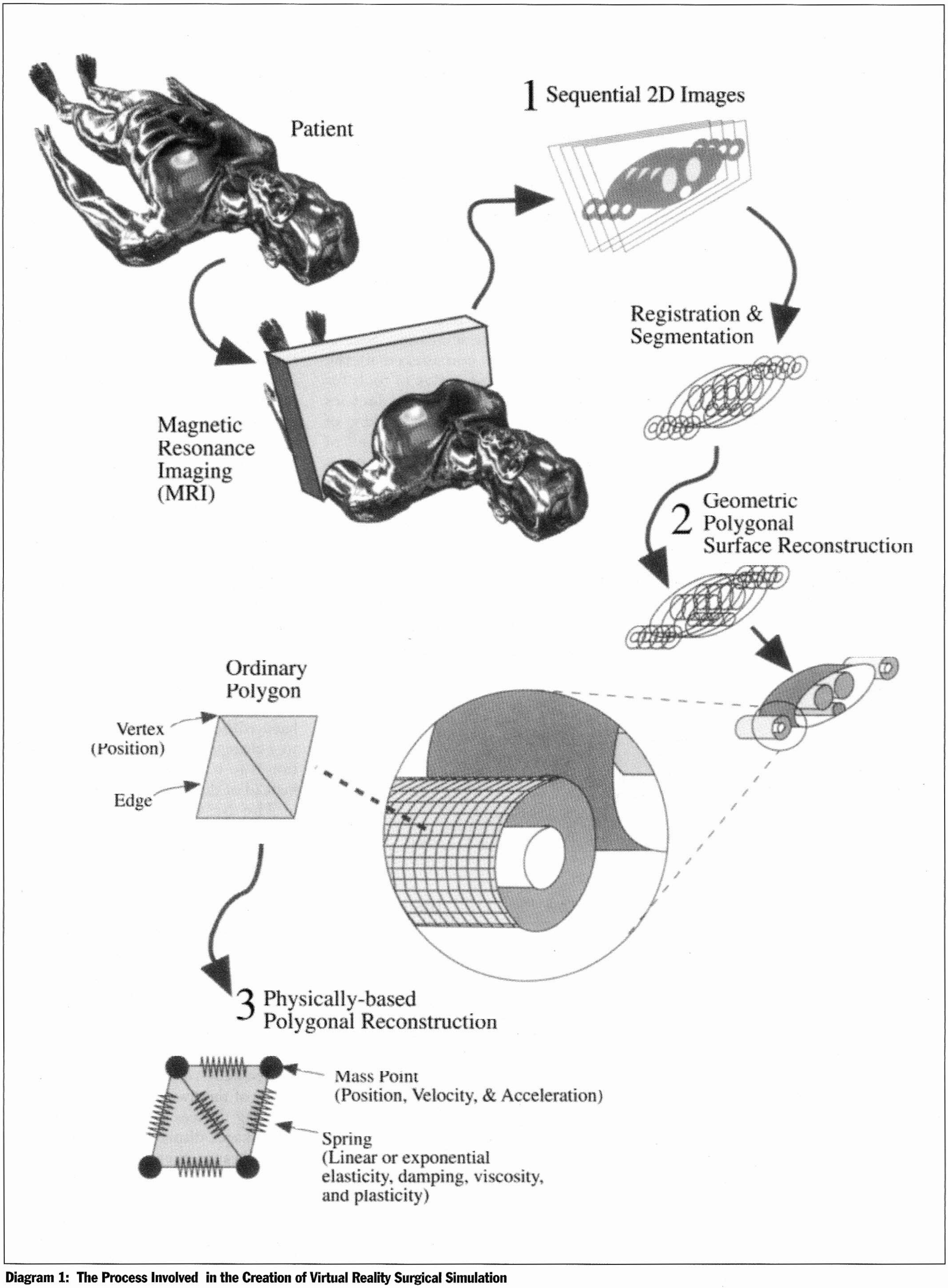

Diagram 1: The Process Involved in the Creation of Virtual Reality Surgical Simulation

• Collision detection. The system must offer the ability to detect

1. the interaction of surgical instruments with the tissues
2. the tissues interacting amongst themselves.

• Replication of tissue behavior. The system must replicate the physics of tissues in so far as these physics pertain to the manipulation of the tissue by the surgical instruments. The systems must also replicate the changes in tissue characteristics which have occurred secondary to trauma.

• Modeling physiological changes which occur after significant injury as well as the changes that occur as a result of surgical intervention (eg, changes in blood vessel color, pulse, and diameter secondary to decreased blood volume secondary to vascular depletion).

To enhance the educational experience, the surgeon must be informed when the wrong anatomic structure is manipulated. If the surgeon resects the incorrect portion of a particular structure, the simulator visually highlights the region where they should have cut and tells the user (using digital audio) that an error has occurred. In addition, the sequence of the operation is very important. For example, if a surgeon forgets to clamp a vessel before transection, a 'bleeder' will occur.

Tool Simulation

To accurately simulate the interaction between the surgeon and the surgical instrumentation, attention is needed on the design of proxy surgical instruments which allow the surgeon to interact with the simulation. Several factors must be considered in the design and implementation of tools for surgical simulation. These factors include: rapid and accurate tracking of instrument position. Realistic 'feel' of the instruments and provisions for tactile feedback are all important in the design of simulations.

Surgical instrumentation is fitted with appropriate sensors to enable the system to track the instruments orientation in space. These sensors also allow the computer to determine whether the instruments are open or closed. Our research (Table 1) indicates that the optimal position-tracking devices involve the use of direct mechanical coupling with optical position sensing; electronics similar to that of a computer mouse. This technology is relatively inexpensive, reliable, accurate, and has minimal lag-time between instrument movement and display.

Two basic approaches for interaction with simulation systems exist: those which track hand position and systems which track surgical instrument position. Each of these methods has to be carefully considered prior to the design of a simulator system. While hand-tracking methods (eg, the use of a special tracking 'glove') allow the greatest flexibility for interacting with a wide range of different 'virtual surgical implements' by allowing the user to reach out, grab, and interact with the different implements. Although these systems allow for a high degree of flexibility in the implementation of surgical simulation; they suffer from a number of draw-backs. The first consideration is that a surgical instrument can move in a users hand without any feedback with regard to a change in position. The ideal solution is to track the surgical instrument instead of the surgeons' hand position.

The first step in the design of appropriate simulation tools is to allow accurate and realistic surgical simulation. Several different methods of tracking the position of the instruments are available. After exploration of the different tracking options and using the criteria of tracking accuracy, reliability, range of motion, and ability to integrate 'tactile feedback' into a tracking system, the best solution for tracking was provided by direct mechanical linkage (Table 1).

Accuracy refers to the spatial resolution of the tracking device. Note that tracking devices with direct mechanical linkages display the highest degree of accuracy; these devices typically have a spatial resolution of .0001 inches. Range of motion is determined by the ability of the device to track position in a given volume of space. Limitations in range of motion can be dictated by mechanical constraints (eg,

SURGICAL TRACKING INPUT DEVICE TYPE VERSUS SPECIFICATIONS.

	Direct-Mechanical Linkage	Ultrasonic	Electro-magnetic
Accuracy	High	Low	Medium
Range of Motion	Limited by device (mechanical engineering)	Limited to line of sight	Limited
Ability to integrate tactile feedback	Very good	Poor	Poor
Reliability	High	Low	Low
Cost	Medium	Low	High
Noise	Very low	High (subject to reflections from walls and other acoustic interference).	Medium (some systems subject to interference with metal objects and other electro-magnetic systems (e.g., computer monitors)).
Lag-time	Minimal	Moderate	Moderate

Table 1.

direct-mechanical linkage) versus electromagnetic devices which are limited by the ability of the devices to produce and detect an electromagnetic field (typically three to six feet). Noise refers to the amount of extraneous information that a given system provides. Lag-time refers to the time interval between change in position of the device and the speed with which this spatial change is reported to the computer.

Tactile Feedback

The additional of tactile feedback to a surgical training system is important to the training. Systems which employ direct mechanical linkage allow physical connection to tactile feedback actuators which in turn provide the feedback to the surgeon. The software environment under development is 'tactile-feedback ready.' The surgical field is modeled using physics and the software has the appropriate software libraries to effect tactile feedback.

Determining the Degrees of Force Feedback for a Surgical Simulation System.

Once the appropriate techniques for surgical instrument tracking and tactile feedback have been established, it is them important to determine the magnitude and direction of the tactile feedback to be used during the simulation. Tactile feedback technology is still in its infancy, each system represents a prototype and as a result, it is important to minimize the number of degrees of freedom in the system to keep both the cost and complexity to a minimum while keeping the optimal educational value. A degree of freedom is equivalent to x,y,z coordinates. Each of these coordinates can have a positive or negative value; hence, there are six-degrees of freedom.

Measurements, Qualitative, and Quantitative Determinations of Surgical Requirements for Surgical Simulations

With laparoscopic procedures, as opposed to open procedures, there is a minimum amount of tactile feedback provided during the procedure. As a result, our first virtual reality instrument designs did not integrate tactile feedback.

In order to facilitate the inclusion of tactile feedback, the first step is to make measurements from the actual instruments during the performance of the surgery. These measurements can give the magnitude of the forces involved during the surgery. In addition to these surgical measurements, it is also be important to collect information about the specific degrees of freedom which are most important in the performance of surgery.

Surgical Simulations Completed to Date:

Our initial work involved the development of a 'virtual abdomen,' which was displayed in the Merck & Co. booth at the American Urological Association meeting. The virtual abdomen or 'uro man' could be rotated around using a SpaceBall (a three-dimensional mouse). 'Uro man' was displayed in three-dimensions using special software to create left and right eye views displayed stereoscopically using Stereographics (San Rafael, CA) Crystal Eyes active matrix liquid crystal shutter glasses. The software ran on the world's fastest graphics computer, the SGI Reality Engine.

Drs. Glenn Preminger and Richard Babayan, Professors of Urology at Duke and Boston University, respectively, were named as the official liaisons of the Education Committee of The American Urological Association (AUA) with the project. The AUA Education committee is under the direction of Dr. Joseph Corriere. The AUA Office of Education strongly believes that surgical simulation will play an increasingly important role in surgical training.[8] During the first AUA conference, a survey was distributed to over 400 urologists which asked their opinion as to the future applications of virtual reality in urologic surgery. The overwhelming response of the urologists was that they saw the potential of virtual reality in revolutionizing surgical training. With confirmation that we had both identified a niche market and made in roads into it, we went after a more challenging goal - the creation of a virtual reality surgical simulation. An initial procedure was selected, a laparoscopic lymph node dissection.

After one year of research and development efforts, the laparoscopic lymph node dissection simulation software was completed. The system was shown at the most recent American Urological Association meeting in San Francisco, it consisted of the same hardware as was shown in the prior meeting with the addition of a custom fabricated laparoscopic input device and a large rear-screen projection system. The projection system enabled many physicians to simultaneously view and participate in the simulation at the same time.

Audio narration and feedback was provided by interactive compact disc (CD). When the user attempted to cut the wrong anatomic structure, the computer would play the appropriate portion of the CD which would tell the user to move the surgical instrument to the position indicated with a three-dimensional cursor.

The virtual reality surgical input device integrates actual surgical devices to be used to interact with the virtual surgical field. This device was created by equipping the surgical tools with sensors which feed back their relative position as well as whether or not the instrument handle was open, closed, or somewhere in between. This interface was ideal for surgical interaction - making the simulation as close as possible to the actual procedure. The system uses direct mechanical coupling with optical position sensing. This technology is relatively inexpensive, reliable, accurate and has minimal lag-time between instrument movement and display.

In parallel with these efforts, we simulated other procedures, including an angioplasty procedure (sponsored by Marion Merrell Dow). This simulation allows the user to use a simulated balloon catheter and to practice angioplasty. The software allows for various complications including transection of the coronary vessels, rupture of the balloon, as well as resistive feedback to the end-user. A specially designed catheter, equipped with position sensors and feedback devices was constructed to afford a high-fidelity simulation of the procedure.

The Future of Virtual Reality Surgical Simulation

For procedures, such as removing a gallbladder or appendix, much of the current training time is spent waiting to observe experienced clinicians. A surgical resident can spend years before he/she does more than observe. This waiting process is costly, provides little challenge or incentive to the surgical student, and is less than advantageous for the patient.

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Without an educational evaluation component of laparoscopic surgical simulation, few options exist for monitoring surgical skill outside of patient outcome data. For example, Dent[1] mentions that:

The quality of a surgeon's performance in laparoscopic procedures, as in all other surgical procedures, should be monitored through existing quality assurance mechanisms in the individual hospital. Proctoring, additional training, or even restriction of surgical privileges may be required if poor outcomes or high complication rates are identified."

If it were possible to identify surgeons whose skills were not up to the standard of care using computer based evaluation, skill assessment could be screened using simulation results rather than patient outcome data.

Clinical privileges

Individual hospital governing boards are responsible for developing their own mechanism and criteria for granting specific clinical privileges. Frequently, hospitals adopt "national" standards developed by specialty boards or specialty societies.

The Society of American Gastrointestinal Endoscopic Surgeons' (SAGES) guidelines state that:[4]

"surgeons who are experienced in operating upon abdominal organs are familiar with anatomy, tissue tolerance, organ compliance, and pathological processes and should readily develop laparoscopic proficiency... "

Surgical simulation allows for both a review of anatomy and an increased facility to practice vital hand-eye-

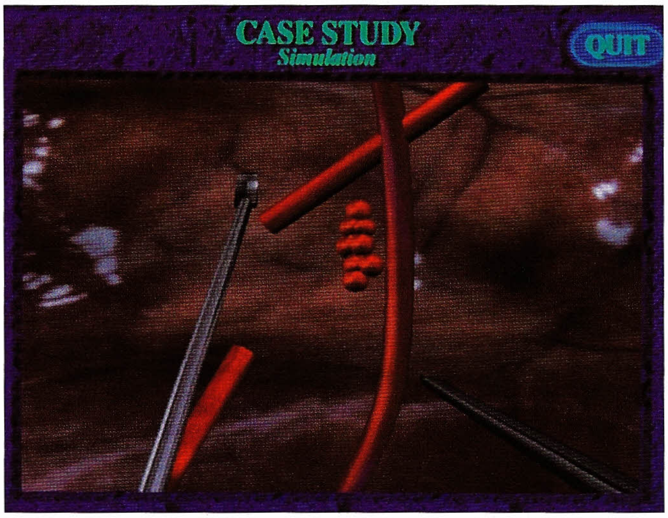

Figure 1: Virtual surgical instruments in simulated surgical field. These illustrations are output of the RealityEngine computer and were stereoscopically displayed during the medical conference. During the simulation, the user can manipulate a variety of instruments, in this frame, the clamps are about to be used. The instrumentation allows the user to manipulate the virtual tissues and instrumentation from any angle in 3-D.

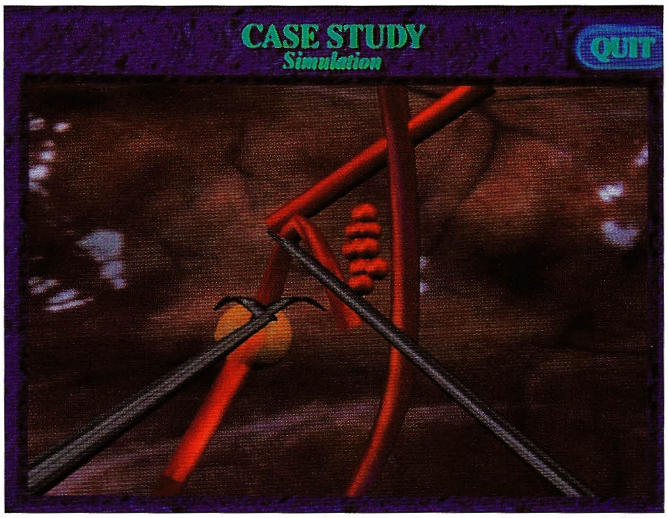

Figure 2: Cutting an anatomic structure using the virtual input device which is controlled by actual instrumentation. Because the instruments are computer aided models, an array of hundreds of instruments can be selected and used during a procedure. During the simulated procedure, hints can be given to the user with regard as to where on a vessel the user should cut. This image shows that the computer is indicating (using yellow spheres) an anatomic region of interest.

Figure 3: Over four thousand urologists used and observed the software during The American Urologic Association meeting in San Francisco. The urologic surgeons donned CrystalEyes glasses (Stereographics Corp.), allowing the physicians to see the anatomy in three-dimensions.

are required in laparoscopic surgery as Dent has further observed:[5]

"Practice using a pelvi-trainer facilitates the awkward technical maneuvers of laparoscopic surgery, but residents growing up in the "Nintendo era" assimilate the hand-screen-eye coordination required for these procedures more rapidly than their attending surgeons."

Current surgical simulations run on machines which cost over $150,000. While this price may seem prohibitive, it represents a significant change from the need to use a machine which cost over $200,000 just two years ago. As processor capabilities increase and the cost of the computers continue to drop, we anticipate that desktop computers with price tags of less than $5,000, will soon have adequate capabilities to allow for realistic surgical simulation. At this price, these simulations will be available for every area in health care from the surgeon to the nurse practitioner.

Surgical simulation systems will serve several purposes. Firstly, they will be useful for physician training to supplement and then replace the use of animals for surgical procedural training. Secondly, they will be used for physician certification - insuring a base level of competency and exposure to different surgical scenarios and anatomic variations as well as hand-eye coordination. In addition, the systems will assist in patient education - as the graphical representations of diseases and surgical procedures are language independent and precisely show the pathology and surgical techniques involved for specific operations. From a training perspective, we have seen automated training become the de facto standard for pilot, naval training and many other aspects of military training. Medicine appears to be a field that can benefit tremendously from virtual reality based educational experiences which allow physicians to practice medical procedures prior to patient contact.

Figure 4: Surgeon using High Techsplanations surgical simulator technology at The American Urologic Association (AUA) conference, held in the Moscone Center in San Francisco. Over 4,500 urologists experienced the simulator during the four and one-half day medical conference—making the exhibit the largest single draw on the trade show floor. Many surgeons were intrigued with the technology and its implications for training and certification.

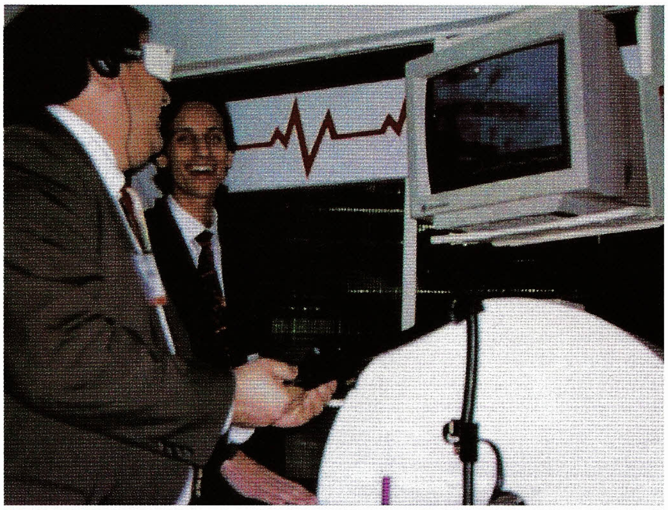

Figure 5: A cardiologist is seen performing a 'virtual cardiac catheterization' during the American College of Cardiology Conference (ACC) in Atlanta, Georgia. The ACC is one of the largest medical conferences with over 35,000 attendees.

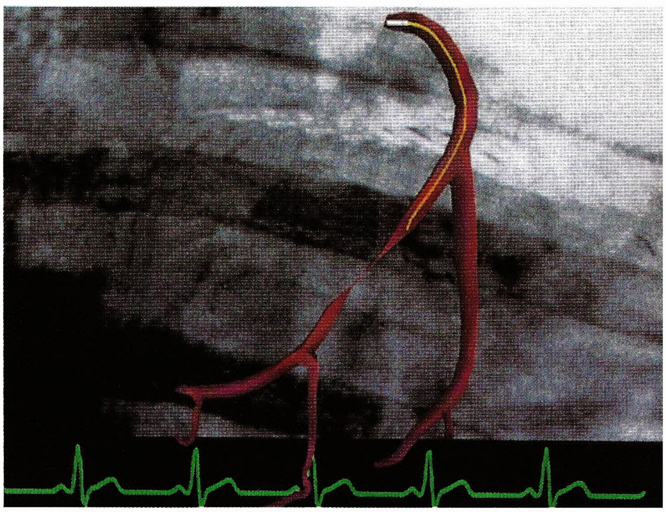

Figure 6: Screen captured from the virtual reality program. 'Virtual catheter' is in the process of being placed to the site of the occlusion. Note simulated ECG tracing at the bottom of the screen.

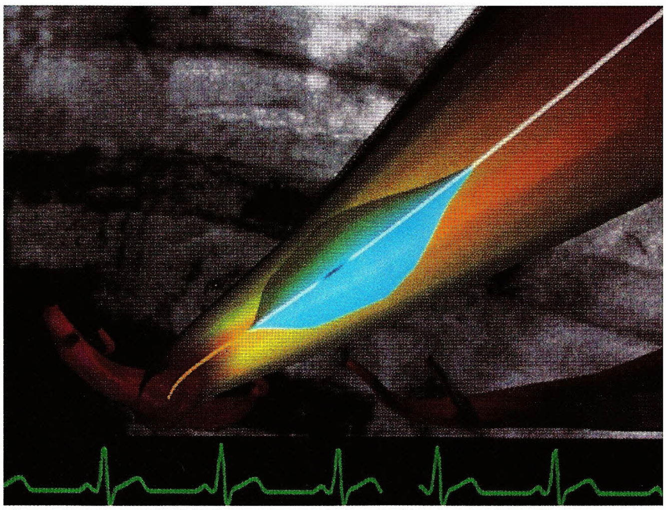

Figure 7: The virtual balloon is now inflated with depression of the pressure sensitive button located on the 'virtual catheter.' With successful dilation of the vessel, the physician can then see that the blood flows freely past the prior area of blockage.

ACKNOWLEDGMENTS

The authors wish to thank Merck & Co, Inc., Marion Merrell Dow, The National Institutes of Health, and The Advanced Research Program Agency (ARPA). The authors would also like to thank the efforts of Rakesh Raju and Alan Milman in this effort. STI

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