Virtual Reality Surgery: Implementation of a Coronary Angioplasty Training Simulator

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Present surgical education relies on a combination of observation, peer review, and practice on cadavers and animals. In contrast, simulation technology, known as "virtual reality," offers the ability to practice hands-on surgical procedures in computer models that exhibit physical and physiological characteristics of living humans.

Although the airline industry and Department of Defense have used flight and battlefield simulators for many years, several technical challenges have limited the use of computer-based simulation technology in medical education. A flight simulator is much easier to implement than a surgical simulator. The terrain of the ground is fixed and rigid, and the plane simply moves through a path above this terrain. A surgical simulator involves much more complexity than a flight simulator. For example, the terrain of the body–the internal organs–must allow for interaction; they must flex and be able to be cut and re-attached. The organs in the body must be programmed with "behaviors" and basic principles of physics so they "know" what to do when they are cut, tugged, stretched, etc. In addition, the surgical simulator must have a knowledge of how each instrument interacts with the tissues.

This work describes, as an example of the new technology, an approach to a second generation of coronary angioplasty simulator that contains the physical and physiological attributes to make it become a useful training tool for cardiologists. Advances in computer modeling, combined with the recent availability of detailed anatomical data from sources such as the National Library of Medicine's Visible Human Project, make feasible the creation of simulations that are authentic reproductions of actual surgical procedures.

Virtual reality technology holds tremendous promise for surgical training because it offers the physician the opportunity to practice in an environment where mistakes do not adversely affect patients. An optimal training simulator should accurately replicate the physical and physiological properties of the real procedure. In addition, it should offer the ability automatically to

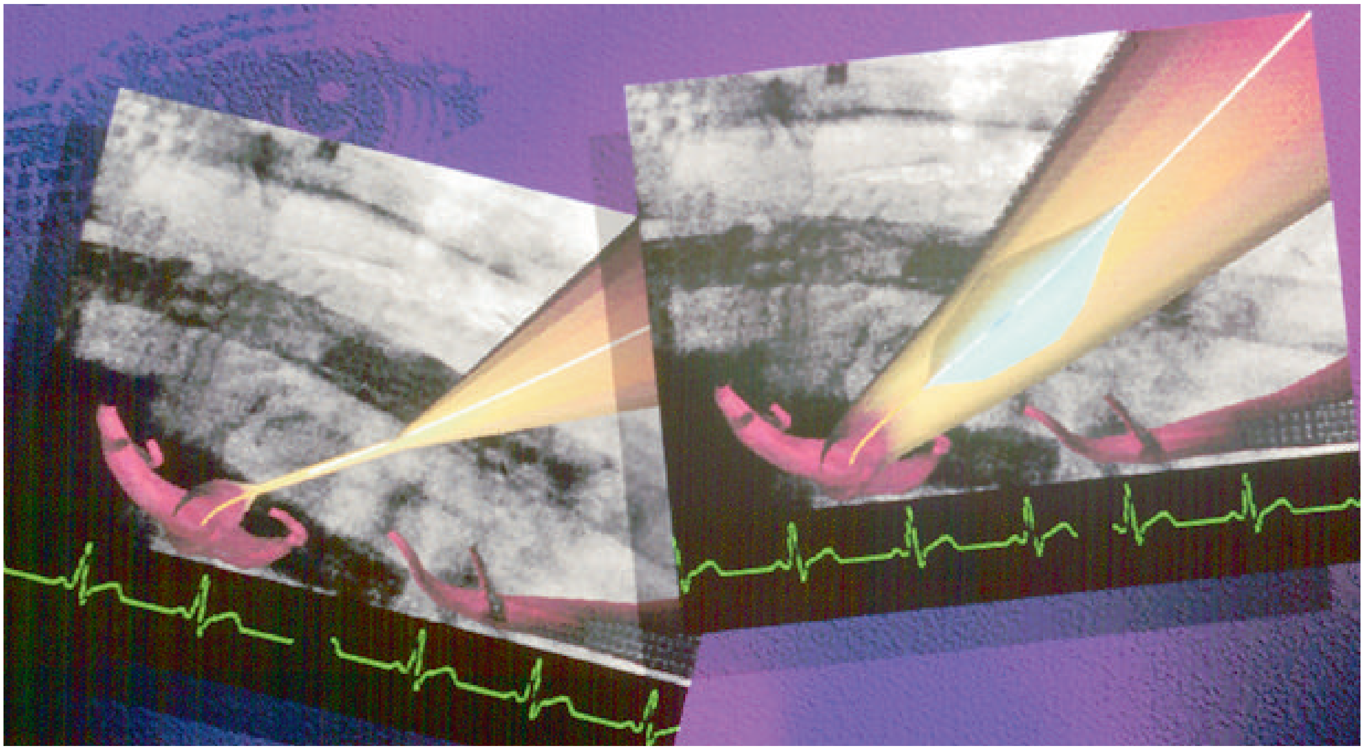

Figure 1. Images taken from the computer screen of the prototype angioplasty simulator. The images depict inflation of a balloon catheter within an occluded blood vessel, along with simulated ECG tracings.

track and evaluate performance, provide the option of different procedural scenarios, and simulate a range of surgical complications and anatomical anomalies.

Improvement in the techniques for both training and treating the complications of coronary artery disease can have enormous impacts in improving healthcare delivery. In the United States, the complications of atherosclerosis account for about one-half of all deaths and for about one-third of deaths in persons between 35 and 65 years of age. Approximately three-fourths of atherosclerosis-related deaths are the result of coronary artery disease (also termed ischemic heart disease). Atherosclerosis-related diseases are also the leading cause of permanent disability and account for more patient-days of hospitalization than any other illness. Several techniques have been developed both to assess the condition of the coronary vessels (e.g., angiography) and to treat the occlusion of the vessels (angioplasty and stent placement). Angiography is utilized during angioplasty, and both angiography and angioplasty are used during stent placement.

Percutaneous transluminal coronary angioplasty (PTCA) was first performed in humans in 1977[1] and has become an established, effective mode of therapy for certain patients with coronary artery disease.[2,3,4] In this procedure, a balloon-tipped catheter is passed percutaneously and maneuvered across an area of stenosis in the coronary artery. The balloon is then inflated under pressure, causing dilatation of the stenotic area. Stent manipulation has been identified as a priority for surgical training by the NIH. PTCA involves a "learning curve," as The National Heart, Lung and Blood Institute has sponsored a registry of patients undergoing PTCA. This registry indicates that the overall success rate has risen from 67% (1977 to 1981) to 88% (1985 to 1986).[3]

The mortality for patients undergoing PTCA is now about 1%, and about 4% of patients have a complication, such as prolonged angina or myocardial infarction, that requires emergency coronary artery bypass surgery. In about 20% of patients, the affected artery becomes stenotic again, usually within six months.[4] These patients are excellent candidates for a repeat angioplasty procedure, as well as stent placement. Improvement is sustained in more than 70% of patients in whom dilatation was initially successful. Percutaneous transluminal coronary angioplasty is generally applied to single-vessel disease but can also be used effectively in patients with multivessel disease and in patients with stenosis of coronary artery vein bypass grafts. Examination of all of the risk factors surrounding coronary angioplasty shows that standardized methods for procedural training would provide increased means for physicians to practice the technique, allow improved initial exposure to the technique, and allow practice of difficult scenarios without patient risk.

We have developed a prototype simulator, supported by funding from Marion Merrell Dow, Inc., which consists of a trade show demonstration of the application of virtual reality technology to angioplasty (Fig. 1). From this work, the following observations were made: there is significant market interest among cardiologists, hospital administrators, insurance representatives, and hospital information managers in the use of a virtual reality system to enhance initial training and for maintenance of angioplasty skills. In terms of technical feasibility, the Silicon Graphics, Inc. (SGI), workstation was capable of rendering the structure of the vasculature in adequate detail for depicting the coronary anatomy for instructional purposes. In addition, the system could maintain real-time frame rates (of greater than 15 frames per second) while supporting tracking a catheter-like input device with tactile

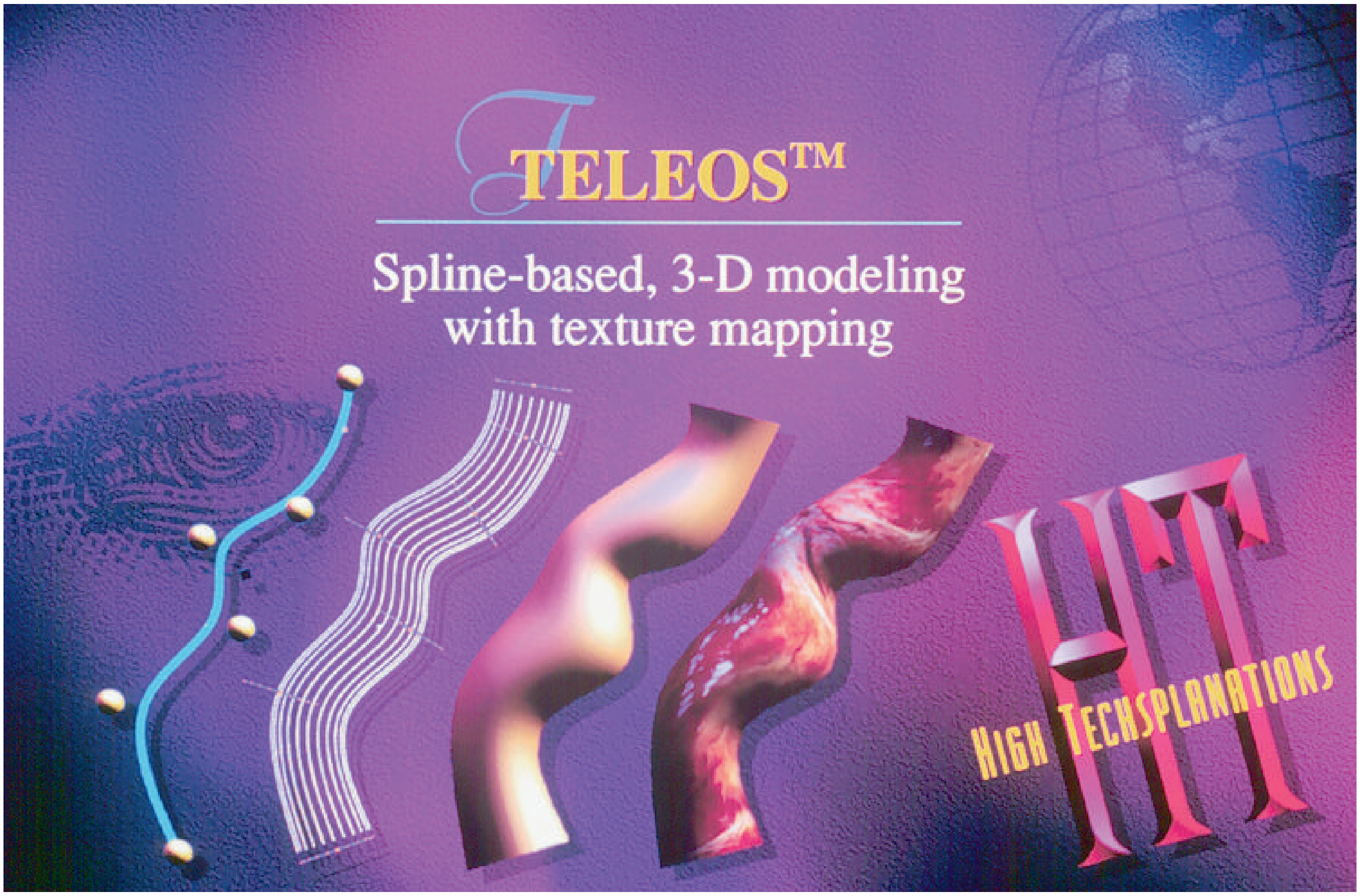

Figure 2. Representation of the building of a structure within Teleos™, progressing from a cubic spline with control points, through wireframe, contouring and texture-mapped models.

feedback. This preliminary work indicates technical feasibility for both graphical and tactile feedback on a high end workstation. With this understanding, we have assessed the feasibility of developing educationally efficacious software intended to teach and assess clinical skills at angiography, angioplasty, and stent placement.

THE NEED FOR ACCURATE PHYSIOLOGICAL MODELING

By far the greatest challenge is to develop a training simulator that provides a physiologically realistic simulation so that it offers a positive training experience. If elements of the simulation lack the accurate physical and physiological properties of the real surgical procedure, the user might develop an inappropriate skill set. For example, if the degree of force necessary to position the balloon catheter in the area of the occlusion in the simulation is greater than that in the actual procedure, the physician may be trained to apply inappropriate force–leading to rupture of the vessel. Thus, it is important to accurately determine physiological realism in the context of positive training. Specific physiological issues surrounding cardiac catheterization include blood flow, heart rate and contractility, and vessel dynamics that may be primary or secondarily altered by the pathology or the surgical intervention. Realistic physiological modeling can be accomplished in several ways. First and foremost, it is appropriate to use proper evaluation methods for obtaining feedback from cardiologists to adjust the physical and physiological parameters of the simulation. Second, it is feasible to use instruments (e.g., transducers) for the accurate measurement of tissue characteristics and physiological variables from within the vasculature. Finally, the opportunity to work directly with the manufacturers of angioplasty devices ensures that the instrument interface provides realistic simulation and tactile feedback consistent with real-world devices.

TELEOS™ - A TOOLKIT FOR AUTHORING SURGICAL SIMULATIONS

The objective of creating a computer-simulated virtual environment for medical training is to provide a level of training not possible using traditional methods. In addition to its utility for developing educational content, we have created a software authoring toolkit called TELEOS™. TELEOS™ facilitates the development of medical simulations for training and for the objective certification of surgeons. TELEOS™ will also provide for patient-specific preoperative rehearsal and virtual reality exploratory diagnostic surgery–significantly reducing operative risk. Only those virtual environments that offer sufficient realism will constitute a commercially viable alternative to established practice on cadavers, animals, and patients. Realism in the context of virtual environments for medical training relates to how the anatomical structures appear, how life-like the interaction is with the anatomy, and how it behaves when one interacts with the anatomy.

Objects created in TELEOS™ have an underlying structure based on Newtonian physics, while the visible structure is based upon geometric relationships such as cubic splines linked to the physical structure (Fig. 2). In a virtual environment, the objects have a physically-based behavior which allows them to react to a user in a realistic manner. In addition, models can be assigned animated subroutines to simulate physiological properties such as cardiac contractility.

The TELEOS™ Authoring Software has the following specific features:

- Modeling 3-D, interactive objects
- Support for "cutting" virtual objects
- Particle system dynamics
- Flexible body dynamics
- Volumetric, 3-D display (including isosurfaces and 3-D texture mapping)
- Capability for import and display of standard 3-D file formats
- Texture mapping
- Shading (Gouraud and flat)
- Collision detection for rigid and deformable objects
- Scalable architecture to support hardware with different computational and graphical capabilities
- Support for three-dimensional input devices (including catheters, endoscopes, joysticks, and position sensors)
- Support for clipping planes
- Support for stereoscopic viewing
- Capabilities for creating models which are optimized for both manipulation and rapid display in a "virtual world"
- Variable level of detail support for maintaining real-time frame rates
- Presence of both a graphical authoring environment and a playback-only system

ANATOMICAL MODELING AND GEOMETRIC RECONSTRUCTION

The anatomical data needed for modeling the coronary arteries can be derived from several sources. First and foremost is the data set generated from the Visible Human program at the National Library of Medicine. Other sources of information can include magnetic resonance (MR) or computerized tomography (CT) data. The outlines of the cross sections of objects can be extracted by manually tracing the periphery of the object in each image or by using semiautomated procedures. Once the outlines of all the cross sections of different objects are extracted from MR, CT, or the National Library of Medicine's Visible Human Project data, the scene is reconstructed in three dimensions as geometric (polygonal) surface models for each object. This is achieved by connecting corresponding points along the outline of sequential cross sections to produce surface patches of polygonal meshes.

As part of the initial development of the next phase of the coronary angioplasty simulator, sample sections from the Visible Human Project photographic data will be obtained and examined. This photographic data can serve as an initial basis for texture to enhance the photorealism of the simulated coronary anatomy. To evaluate the accuracy of the resulting three-dimensional objects, the surface reconstructions of the tissues are displayed in both wire-frame and surface-shaded modes, and a volumetric reconstruction of the data is to be overlaid. Registration between the two reconstructions occurs by lining up the edges of the scan boundaries, and hence the volumetric and contour-based reconstructions are in the same coordinate space. The reconstructed data is examined to evaluate image segmentation accuracy. TELEOS™ allows quantitative measurements between the data-sets to ensure that accuracy is maintained.

DECREASED HARDWARE COSTS AND INCREASED CPU SPEED WILL LEAD TO WIDESPREAD DISTRIBUTION OF THE CORONARY ANGIOPLASTY SIMULATOR

The initial version of the coronary angioplasty simulator is designed to run on an SGI Indigo2 Extreme workstation. Because SGI hardware is binary-compatible throughout the range of products, this strategy enables our simulation software to run on existing hardware as well as to be easily adapted to run on future machines with multiple, higher performance CPUs and future higher performance graphics subsystems. While new technologies are constantly being introduced and these new technologies are expensive, the hardware-based texture mapping, transparency, and real-time graphics throughput is currently available under $50,000. There will always be faster graphics options for computers, but the necessary performance features are currently available at a price which makes the sale of surgical simulator software feasible and attractive.

The Project Reality/Ultra64 machine is a product to be created through the collaborative efforts of SGI and Nintendo. This system, currently available in arcades, will be available at an approximately $250 price point for the consumer game in mid-1996. This system will have many of the performance features of today's $200,000 RealityEngine, with real-time texture mapping and rapid polygon manipulation. This performance will be achieved through the use of custom graphics chips developed by SGI. The Ultra64 also contains a RISC CPU that outperforms current Intel Pentium and Motorola PowerPC processors. The availability of these features in game machines emphasizes the widespread availability of technology which will soon have performance adequate to support real-time surgical simulations.

Eventually, the coronary angioplasty simulator will be configured to run on a personal computer. This requires the design of software that will allow adequate graphical representation, interactivity, and tactile-feedback to create a realistic simulation on a PC. With the advent of a new generation of 3-D graphics boards for the PC, it may soon be possible to expect full 3-D performance characteristics similar to the current generation of SGI machines.

THE ROLE OF HUMAN FACTORS IN THE EVALUATION OF SURGICAL SIMULATION

No matter how impressive the display and interactive capabilities afforded by surgical simulation, there are of course a set of issues to be considered that are distinctly human. For example, does the experience of surgical simulation lead to better surgical performance in the operating room? How does one, in fact, actually measure surgical performance? By what criteria does one judge how fast the surgical resident is learning the craft, both acquiring the requisite knowledge and developing the appropriate psychomotor and decision-making skills?

Once a student advances beyond the classroom phase of instruction, most surgical training today is "hands-on," with the resident taking on increasing responsibilities for treating patients, under the watchful eye of an attending surgeon. This assessment of skills, and of progress in training, is subjective, being based largely on the personal observations of the supervisor. The criteria used in making evaluative judgments are thus likely to be subjective, and can be somewhat variable from physician to physician; or they are relatively gross indices based on outcome: Do the patient's vital signs and symptoms suggest that a given surgical manipulation had the desired effect, or does the long-term patient outcome indicate that the surgical intervention was a success?

Assessing the efficacy of surgical simulation forces us to address these issues and enables the profession to consider the possibility of more objective measures of competency. By embedding performance measures in the simulation software, developers can provide feedback to students, based not just on outcome but on progress as well. It is also possible quantitatively to compare the user's session–the timing and accuracy of all of its aspects–with the experts' judgments of what constitutes an ideal performance. The logical extensions of this capability include real-time "coaching" algorithms, quantitative historical data on how a student is progressing along a desired "learning curve," and objective criteria for certifying the competency of a surgical candidate.

The power that virtual reality-based surgical simulation methods afford in speeding up the training of surgeons and improving the quality of training has yet to be demonstrated. The technology is so new that meaningful data are just now starting to be collected. In fact, we are presently determining the set of performance measures that capture the important facets of various surgical procedures and acquiring the expert knowledge that will allow us to set performance criteria. Some guidance from other settings is currently under examination–for example, from aviation, military training, and process control industries.

The "bottom-line," however, will be the extent to which surgeons trained with virtual reality acquire the requisite skills faster, or attain higher levels of competence, than those trained with conventional methods. It is certainly not a given that simulation-based training will necessarily improve performance in the operating room. However, now that the tools for high-fidelity surgical simulation are available, the challenge will be to integrate this powerful methodology seamlessly into the training curriculum.

SUMMARY

A prototype angioplasty simulator has helped to demonstrate the benefits of applying virtual reality technology to medicine for the creation of surgical simulations. The TELEOS™ toolkit has made possible the development of the angioplasty simulator and other training applications in medicine that require, in real time, the physiological and physical properties of actual surgical and medical procedures. New challenges include the refinement of physiological accuracy in the virtual surgical environment and the need for assessment of human performance in meeting the training objectives of surgical simulation. STI

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