Computer-driven flight simulators have been designed to provide an interactive, real-time experience that realistically simulates emergency events for the experienced pilot, offers exposure to new environments (i.e., practice landings at airports new to the pilot), provides fulfillment of recertification requirements, or offers learning experiences for the trainee. The technology required to produce realistic visual simulation previously has required extremely expensive custom-built simulation computers, but now off-the-shelf, high-performance graphics workstations...
make the generation and presentation of realistic simulation imagery in real-time economically possible. Although the current cost of computer hardware to run the appropriate software is expensive, based on the history of computer development it is likely that the cost of the hardware will be reduced significantly in the future. Computer simulations, especially those where real-time visuals are presented as an outcome of a person-in-the-loop interaction, have established their significance in training.1

Ophthalmic surgery is an area that can benefit from such technology. Historically, physicians learn new surgical procedures through observation, practicing on animals and/or donor eyes, and then assisting with, or performing, the procedure on patients under the supervision of an experienced surgeon. Studies have shown that ophthalmology residents can perform cataract–intraocular lens surgery, as well as other procedures, at a safety and efficacy level comparable to community professional standards when given appropriate training, education, and supervision.2–14 In the future, it is anticipated that computer simulation will allow physicians to practice surgical procedures and hone skills in a virtual environment in which (1) there is no risk to patients,15 (2) any errors can be reset immediately by the computer, and (3) the procedure can be reviewed from new, insightful perspectives that are impossible in the real world (e.g., from inside the eye).

Materials and Methods

Eye surgery simulation includes five basic components that are required to support surgical training: (1) an operating station, (2) computer models of the anatomy and the surgical instruments, (3) a tactile feedback system, (4) a position tracking system for the surgical instruments, and (5) software that controls the interaction and updates the visual and tactile feedback.

The operating station is the physical interface between the surgeon and the virtual operating environment. The operating station includes a stereo viewing system and a wrist rest, but instead of looking directly at a real eye, the surgeon interacts with a virtual eye using a virtual surgical instrument controlled by a hand-held Polhemus three-dimensional position tracking stylus (Polhemus, Inc, Colchester, VT) that continuously reports position and orientation to the computer (Fig 1). The tip of the stylus is connected by thin rigid bars to three motors that generate component force feedback in response to the surgical interaction. The simulation interface also includes a dial box and a button box that control instrument selection and viewing options. Using the button box, training sessions can be changed, recorded, and played back. In addition, the models may be reset and outer layers of the eye can be removed to show interior anatomic components. Dials allow rotation of the model so that different views may be observed: changes may be made in the transparency of tissues such as the cornea or lens, the degree of magnification may be changed using a zoom system, and adjustment of stereo viewing parameters may be modified. An instrument activation switch on the stylus controls instrument actions such as opening and closing forceps and scissors. These actions occur instantly upon activation.

The software rapidly cycles through a loop that reads the current instrument status and activates the appropriate graphic and tactile responses. The simulation latency, defined as the period of time between an operator input (stylus movement) and the last pixel of the first field drawn (which reflects that movement of the stylus) is approximately 120 mseconds. Tactile feedback, however, is approximately 300 μseconds because no visual feedback is involved in this aspect. Instrument status includes the type of surgical instrument, whether it is activated (for example, scissors open or closed), and its position and orientation. Four surgical instruments have been modeled: (1) a scalpel, which cuts at the point of application; (2) scissors, which open and close and cut tissue at the point of application; (3) forceps that open and close, allowing one to grasp and pull at the point of application; and (4) a phacoemulsifier that removes the lens (Fig 2).

In the virtual environment, the eye and the surgical instruments exist only as computer models. The eye is represented by a collection of deformable three-dimensional polygonal surface models. Surface models of the sclera, iris, zonules, and retina are texture-mapped with photographic images of these components. The lens and cornea are modeled as semi-transparent surfaces. The graphic images required in the simulation were obtained from videotapes and photographs. The geometric, mechanical, and textural components of the ocular structures of interest were obtained from ocular models and real specimens. Measurements were made of the forces involved in cutting the sclera using strain gauges attached to scalpels that were used to cut into eye bank eyes. Adjustments were made in the simulation to reflect tissue behavior and deformability, as described by experienced surgeons, as accurately as possible at this level of development.

The four surgical instruments used in the simulation were created as simple three-dimensional polygonal surface models using the Wavefront Advanced Visualizer modeling package (Wavefront Technologies, Santa Barbara, CA). An overhead light source included in the simulation produces specular highlights on the ocular components. The texture mapping of photographic images, transparency, and lighting are supported by the Silicon Graphics system (Silicon Graphics, Mountain View, CA). These advanced computer graphics techniques add a high degree of realism to the anatomic models that could not have been achieved in previous generations of computers.

Results

Interaction between the instruments and the eye depends on the instrument per se, the location of the instrument in the anatomy, and the kind of action requested by the surgeon. As the knife makes contact with the external ocular surface, the sclera slightly deforms until the blade
penetrates and starts to cut. The force (or tactile) feedback system produces a compliant resistance as the sclera deforms and then allows the blade to slice through the sclera with a small viscous resistance in the cutting direction after penetration (Fig 2). As the blade is cutting, a strong compliant resistance is generated at the stylus tip in the direction orthogonal (lateral) to the cutting direction to produce the same type of resistance that would be experienced if the surgeon tried to lift the incision with the flat portion of the blade.

Surgical scissors function similarly to the knife; however, the scissors close and open when the stylus activation switch is depressed and released, respectively (Fig 2). After an incision is made, the scleral surface is redefined to include a wound where the cut was made. Forceps can be used to grasp the sclera and open the wound (Fig 2). During the grasping action, the simulation software continuously recomputes the deformed surface, based on how far the sclera is stretched. Both visual and force feedback are provided to the user: if the forceps are opened during the tissue-grasping action, the sclera is released, it reverts to its original shape visually, and the resistance is removed. The phacoemulsifier can be inserted through the wound and directed to the lens. During this procedure, resistance is produced to hold the phacoemulsifier in the wound, and another response is produced to simulate contact with the lens. By pressing the instrument activation switch when the phacoemulsifier is in contact with the lens, the resistance changes to viscous to simulate the feel of the vacuum action as the phacoemulsifier removes the clouded lens (Fig 2).

A computer model thus has been developed that is functional and offers features desirable and necessary in such a simulation of ocular surgical procedures. Further work is necessary to enhance different features of the model system, including refinement of the tactile feedback, addition of a second instrument in the operating field, adjustments of the anatomy, elimination of slight time lag between stylus movement and instrument movement in the visual feedback system, and more realistic simulation of the force involved in lens removal. During this next development phase, both novice and trained surgeons will provide feedback on the extent to which the simulation duplicates the surgical experience. Currently, trained surgeons have had only limited use of the model system.

Discussion

Use of the eye surgery simulator would permit the expertise of skilled surgeons to be used to educate less-experienced surgeons, allowing them to learn and practice basic skills for any surgical procedure while being evaluated objectively by an instructor. Similarly, the opportunity exists to simulate infrequently performed surgical situations for experienced surgeons, so that management of these can be practiced. The simulator allows review upon its conclusion, and an idealized method of performing the procedure also can be demonstrated. The entire eye can be modeled with the appropriate structures and viewed from any desired angle. This approach will decrease the need for either animal or human donor eyes as the methodology becomes more fully developed.

Simulation offers great potential for improving medical care through training, instrument design, surgical planning, and support. Residents will use simulators to explore basic anatomy and practice hand–eye coordination for many procedures that currently require training with animal and/or donor eyes. Advanced training will be provided on simulators for experienced surgeons as they try new procedures or experiment with different instru-
ments. When fully developed, therefore, it will allow residents to develop surgical techniques in a harm-proof environment and will allow practitioners to acquire new techniques without compromising patient care. Anatomy can be peeled away, one layer at a time, to show relations among the instruments, the incision, and critical ocular structures. With patient-specific models of the anatomy, surgery could be simulated before it actually is performed on the patient. Optimum instrumentation, approach angle, and depth of incision can be predetermined through practice on the simulator.

The use of computer technology in education is being used increasingly in different fields of medicine, extending from laparoscopic surgery to anesthesia. In the latter, it is being used to improve the management of critical situations. Reconstructive craniofacial surgery also has benefited from the use of surgical simulation based on three-dimensional imaging to display different possible surface configurations after simulated surgical manipulation of the underlying bones. An increase in morbidity and mortality has been observed when unskilled practitioners first begin performing new procedures, thereby stressing the importance of providing some means by which inexperienced, and experienced, surgeons can learn new techniques. Many new procedures are complex and require the acquisition of considerable skills. By providing simulation as a facet of the learning process, an important step in training is achieved.

Use of advanced technology with computer simulators of laparoscopic techniques also is being proposed as a facet of privileging criteria, although this requires the surgeon to move past the initial learning curve and become somewhat proficient with the techniques. The problems to be addressed concerning this use of simulation technology are those inherent in the adoption of any new techniques, namely the establishment of guidelines for credentialing or certifying physicians to perform these procedures. Although use of simulation is common in the airline industry for training pilots and measuring skill levels, its introduction into medicine will require careful consideration. These approaches will not fully replace laboratory-acquired skills, procedure monitoring, and association with those more skilled in a given procedure. The development and adaptation of simulator technology would allow assessment of the technical demands of a new procedure and measurement of a doctor's skills against standardized models. Thus, simulation offers not only a training methodology but also may offer an evaluative technology where accurate, objective assessment of technical skills may be made.

References

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