Computer-Simulated Phacoemulsification

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Objective: To develop a simulator for training in phacoemulsification to be used as a learning device for both beginners and experienced surgeons to shorten the learning curve.
Design: Experimental study.
Methods: The system consists of a personal computer, a 3-dimensional visual interface, a phacoemulsification handpiece, and a nucleus manipulator and foot pedals for control of the phacoemulsification procedure and microscope adjustments. The simulation is based on generalized simulation software that can be also used for the development of other medical simulations.
Main Outcome Measures: Qualitative statements given in a questionnaire. Medical students and ophthalmic surgeons with varying experience of phacoemulsification were tested.
Results: A simulator for training in phacoemulsification has been developed. The surgical procedures can be practiced any number of times, and there is no risk to patients. The efforts of the surgeon can be evaluated objectively.
Conclusions: Studies have shown that the number of complications for an ophthalmic surgeon learning phacoemulsification decreases exponentially, reaching close to the asymptote only after several hundred procedures. Simulator training might shorten the learning period, reduce expensive supervision by an experienced surgeon, and maintain and improve the skills of experienced surgeons. *Ophthalmology 2004;111:693–698 © 2004 by the American Academy of Ophthalmology.*

Recently, personal computers have become powerful enough to permit real-time operator feedback simulation of surgical procedures. This allows a widespread use of virtual reality simulators in ophthalmic surgery for teaching new surgeons and for training experienced surgeons on how to manage peroperative complications. The potential benefits of such simulators could relate to both acquisition and assessment of surgical skills.

We believe phacoemulsification is a good application for simulator training because the operation is a fairly complex procedure requiring extensive training. The procedure is essentially dependent on visual feedback. Tactile feedback is almost absent. Both these factors make phacoemulsification less difficult to simulate. Furthermore, cataract surgery is the most common surgical procedure in the Western world.

Phacoemulsification is usually taught in 2 phases. During phase 1, the student watches surgery performed by a teacher, an experienced colleague. The student may also exercise the procedure on enucleated animal eyes. The duration of the first phase may vary between approximately 6 and 12 months, depending on the type of surgical center, the student's learning speed, and previous experience in ocular surgery. During phase 2, the student operates and the teacher stands by. Because the operation is almost exclusively performed with local anesthesia with the patient awake, the possibilities for the teacher to comment to the student during surgery are limited. Furthermore, because of space constrictions, the teacher has no immediate access to the operating field and cannot easily prevent erroneous manipulations by the student. The duration of the second phase again might vary from approximately 6 to 12 months. Altogether, the teacher and the student might spend more than a year together in the operating room before the student can begin to operate independently.

The phacoemulsification procedure requires relatively complex coordination of hands and feet, and the margins for inaccurate manipulations are small. The success of the operation is highly related to the maintenance of an intact capsular bag. Despite careful training, residents are reported to have an incidence of 5% to 20% of capsular ruptures during their first 200 cases.[1–4] Similar figures have been reported for experienced surgeons learning phacoemulsification.[5,6] A study of 1000 consecutive cases operated by 1 surgeon demonstrated that the number of complications decreases exponentially and that the asymptote is reached after approximately 400 cases.[7] A similar study by another experienced surgeon showed that the asymptote is reached after approximately 1000 cases.[8]

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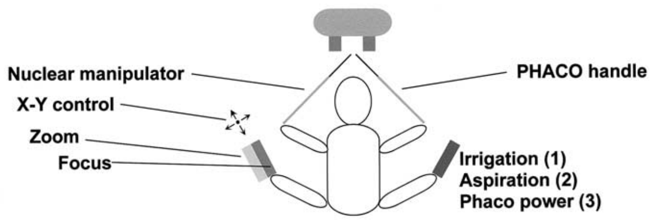

Figure 1. The complex interface between the surgeon and the environment during cataract surgery. PHACO = phacoemulsification.

Efforts should be made to shorten the long learning period for phacoemulsification and to minimize the number of intraoperative complications. There might also be economic gain if the time during which high-volume cataract surgeons are occupied with teaching could be reduced.

Pedagogic feedback is facilitated in simulators, because the metrics calculated intrinsically in the software to run the simulation can be used to give performance feedback to both trainees and teachers. In basic medical education and during the training of residents, medical simulators could be used to make objective assessments of psychomotor skills. Hand-eye coordination may be tested and trained with virtual reality applications.[9] Recently, it was demonstrated that virtual reality training leads to faster adaptation to the psychomotor restrictions encountered by surgeons who operate through small incisions.[10]

Materials and Methods

The complexity of phacoemulsification surgery is indicated in Figure 1. The surgeon gets 3-dimensional visual input from the microscope and must provide feedback reactions with the right hand on the phacoemulsification handpiece (3 space dimensions + rotation), with the left hand on the nucleus manipulator (3 space dimensions + rotation), with the right foot on the pedal controlling irrigation, aspiration, and phacoemulsification (movement in 1 dimension with the function related to the position of the pedal), and with the left foot on the x–y control (2 dimensions), the focus control (1 dimension), and the zoom control (1 dimension).

In the first step, the phacoemulsification procedure was simulated with a nucleus manipulator and a phacoemulsification handpiece for input and a computer screen as a visual feedback interface to the trainee (Laurell CG, et al. Computer-simulated phacoemulsification. SPIE Proc 2001;4245:174–6). In a second step, a 3-dimensional visual interface, software for zooming and x–y positioning with foot pedals, and a computer algorithm for foot pedal real time focusing–defocusing have been developed.

Hardware

A simulator should contain the same transducer complexity for the surgeon as in the real situation. The system developed consists of a personal computer, a 3-dimensional visual interface, a phacoemulsification handpiece, a nucleus manipulator, and foot pedals for control of the phacoemulsification procedure and microscope adjustments (Fig 2). The phacoemulsification handpiece and the nucleus manipulator are mounted with 4 degrees of freedom (3 space dimensions + rotation), with an electronic transducer for each degree of freedom. Similarly, the positions of the foot pedal are sensed with analog electronic transducers. All signals are converted to digital in a personal computer card. The digital signals are used as input in the simulation software.

Three-dimensional Visual Interface

To achieve a 3-dimensional visual interface, the monitor units from a virtual reality helmet (AddVisor 100, Saab Avionics, Sweden) are mounted above the phacoemulsification handpiece and the

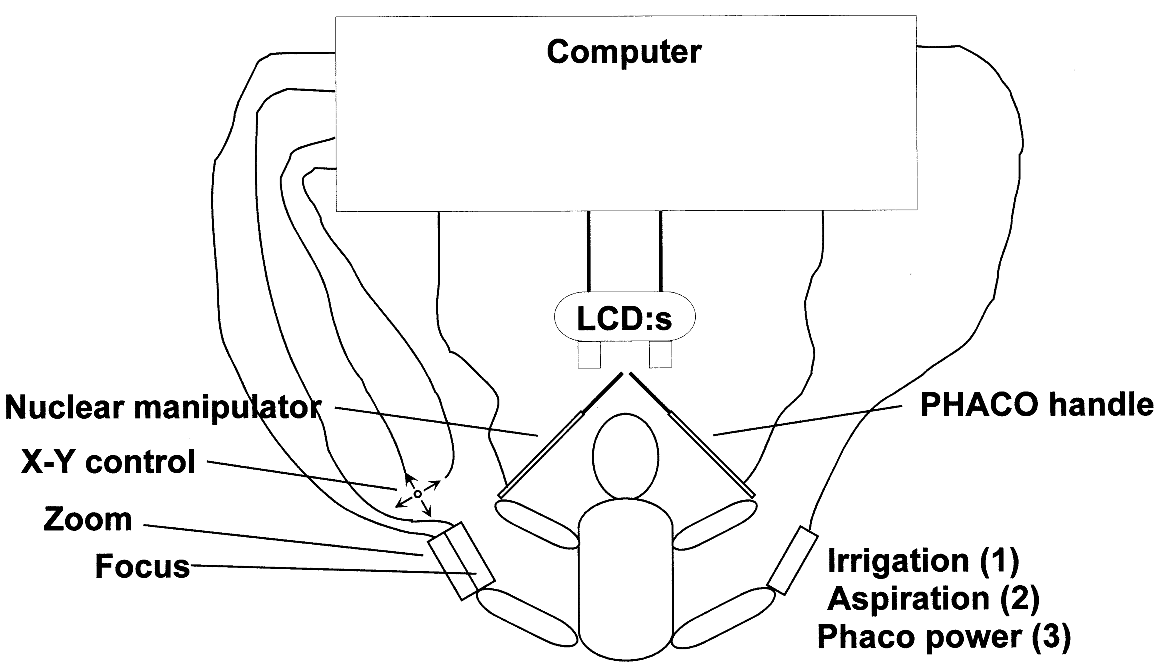

Figure 2. Schematic of simulator with the same interface complexity between surgeon and the environment as in real surgery. LCDs = liquid crystal displays; PHACO = phacoemulsification.

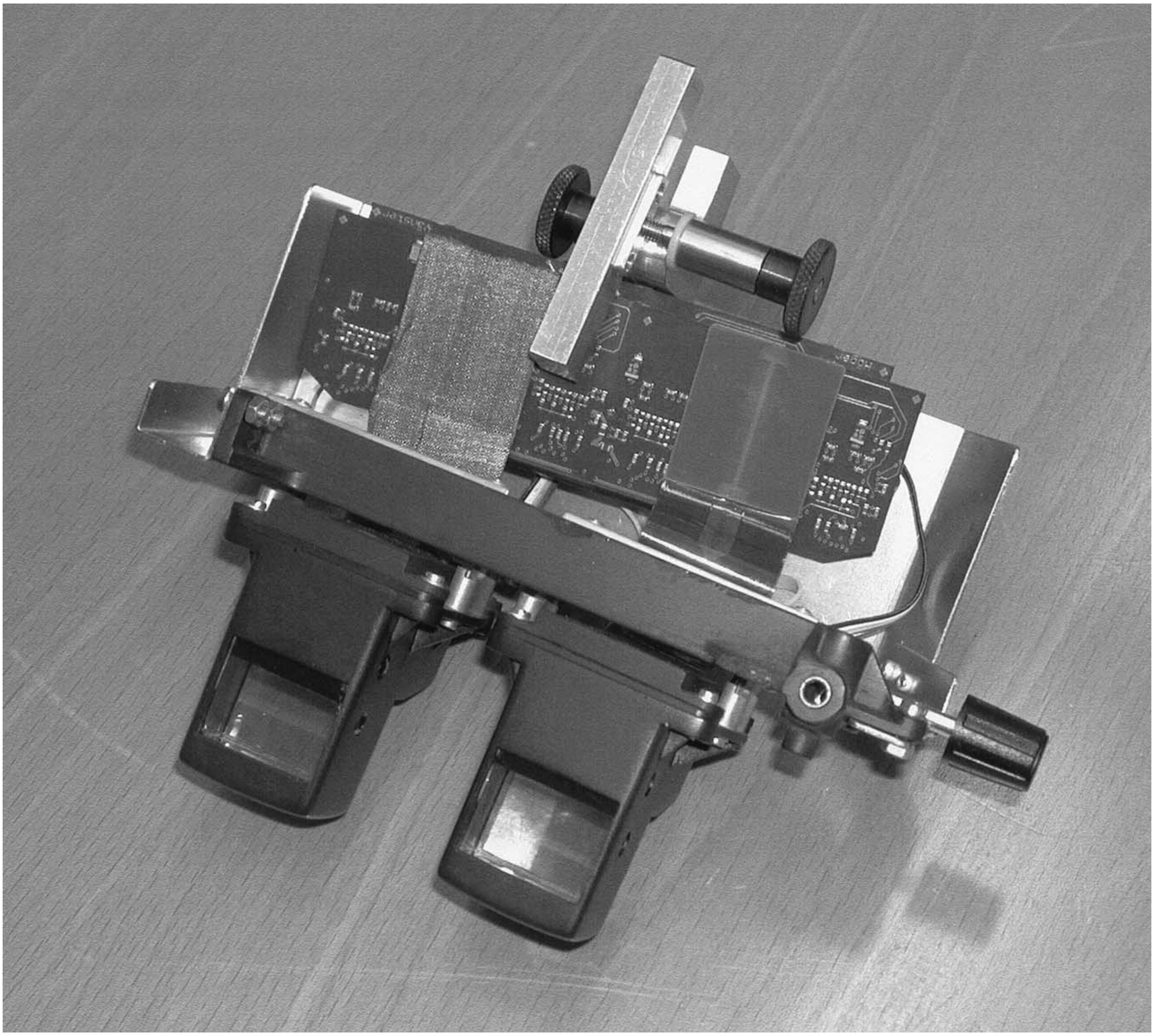

Figure 3. Visual interface for 3-dimensional binocular view.

nucleus manipulator (Fig 3). Each monitor consists of a high-resolution liquid crystal display (LCD). In the simulator system, these units are mounted on a commercial Carl Zeiss (Stockholm, Sweden) microscope stand. There is a forehead phantom for hand support during surgery.

Foot Pedal Control of Phacoemulsification

The position of the transducer for foot pedal control of phacoemulsification power is fed into the algorithm that determines the efficacy of the virtual phacoemulsification process, implying linear response in phacoemulsification power.

Zoom and x–y Positioning

The position of the zoom and x–y is fed from the foot pedal transducer into the software. For zooming, the magnification of the virtual image presented on the LCD is altered. When moving the x–y stick on the foot pedal, the virtual cameras monitoring the eye model are moved in relation to the eye model, thus moving the center of the image on the LCD.

Focusing

The data input is a 3-dimensional model of the surgical field with a defined focal plane. A blurry image and a sharp image of the focal plane are generated.

Averaging over several pixels generates the blurry image. For each pixel the distance between the focal plane and the image is measured. The final image is generated as a mixture of the sharp and the blurred image, using the distance to the focal plane as the weight for luminous intensity of the images.

Software

The simulation is based on generalized simulation software (M-base, Melerit AB, Linköping, Sweden), which is working on top of

Figure 4. Phacoemulsification simulation.

Cosmo3D/Optimizer (Silicon Graphics Inc., Mountain View, CA). On top of M-base, a module has been created for the phacoemulsification procedure.

Mode of Action for Phacoemulsification

A 3-dimensional model of the field of surgery is generated (Fig 4) and presented to the surgeon on the LCDs. The surgeon can sculpt the nucleus with the phacoemulsification handpiece, rotate or push on the nucleus with either of the instruments, divide the nucleus, and aspirate the pieces. The action of the 2 instruments is immediately fed back to the visual interface as image information with an update frequency of 25 Hz, thus directing the next move of the surgeon.

Evaluation of the Simulator

Cataract surgeons of various experience levels tested the realism of the simulator. In a pilot study, 7 medical students, who had passed the course in ophthalmology, were interviewed before and after performing phacoemulsification in the simulator. The study was performed in cooperation with the pedagogic institution of the University of Linköping, Sweden.

Results

A simulator for training in phacoemulsification has been developed. In the simulator, the most important steps in learning the phacoemulsification procedure might be reproduced. Sculpting and dividing of the lens nucleus can be performed in a realistic manner, followed by aspiration of the nuclear fragments. The movements of the pieces of nucleus are similar to real surgery because of simulated flow and aspiration, attracting the lens pieces to the phacoemulsification tip. The hardness of the nucleus (nuclear sclerosis) can be altered freely and correlates to different nuclear colors. Rotation of the nucleus can be made more or less difficult, simulating the situation after ineffective hydrodissection or a loose lens capsule. Breaks in the posterior capsule may be simulated. Total procedure time and total phacoemulsification energy can be measured, and the movements of the instruments inside the eye may be registered by the computer. During the procedure, air bubbles are generated exiting from the irrigation holes in the sleeve of the phacoemulsification handpiece.

According to the structured interviews with the medical students, they were positive regarding the use of medical simulators, because simulators make possible surgical training without risk to patients, and the procedures can be exercised any number of times. The movements on the computer screen were considered to agree with the real movements and felt natural. The students thought that simulators might be used to test disposition and interest for ophthalmic surgery. A rapid understanding of a procedure and its complexity may be achieved. According to the students, realism of function is more important than photorealism of the visual interface. The students stressed the importance of receiving continuous feedback in the form of changes in the picture and text messages, as well as a comprehensive judgment at the end of the procedure. The possible risk of a false feeling of security and the importance of training on real patients were mentioned.

The cataract surgeons found the realism of the simulator adequate for further studies in which the validity and educational value of the device are to be evaluated.

Discussion

The first surgical simulators appeared in the early 1990s.[11] Today, the fast development of information technology and computer graphics presents opportunities to create new tools for surgical training. Virtual reality simulators are known to provide a safe training environment for high-risk work environments. The simulators are available at all times and provide a structured curriculum that can be standardized, repeated, and optimized toward the learner's needs. Skills may be assessed objectively and repeatedly. In addition to the improved training opportunities, simulators might shorten residency training programs and perhaps lower educational expenses.

One problem is that the development of virtual reality applications is expensive and time consuming. Close collaboration among physicians, computer scientists, and engineers is essential. However, the success of virtual reality in pilot and military training suggests strong potential in medical education. Experienced airline pilots maintain their skills continuously through the use of flight simulators.

Until now, surgical education has mainly been based on the apprentice model. The residents gain progressive experience through supervised training on patients. However, this model might fail to provide skill acquisition in an organized fashion. Concerns about cost and risks to patients have been raised, and the importance and potential danger of learning curves have been alluded to.[12] Although alternative training methods such as surgery on artificial eye models and cadaver eyes are available to a certain extent, there are significant drawbacks to these methods. The accessibility to training on pig eyes is limited, and the characteristics of the lens nucleus and capsule in these eyes are different from what we find in human eyes with senile cataract. Sculpting and dividing the nucleus is much more realistic in the simulator, because the lens nucleus of the pig eye is too soft for practicing this procedure. Furthermore, the lens capsule of the pig lens is difficult to break, in sharp contrast to the capsule in senile cataracts. Recently, the risk for transmission of infectious diseases has been said to impose practical problems and increase costs on setting up wet laboratories.

As long as there is a learning curve involved in the training of phacoemulsification, something should be done to improve the situation. However, medical simulators will have to be evaluated carefully to confirm whether virtual reality training improves surgical education. Recently, such training was demonstrated to improve operating room performance during laparoscopic cholecystectomy in human patients. Surgeons trained in a simulator made 6 times fewer errors and were 5 times less likely to injure nontarget tissue according to a randomized, double-masked study (Gallagher T, presented at the Annual Meeting of the American Surgical Association, Hot Springs, Virginia, 2002). Even experienced surgeons with more than 7 years of experience demonstrated a significantly improved performance with the added experience of simulator training. Other recent studies have shown improved skills by residents after training in a bronchoscopy simulator[13] and a laparoscopic simulator.[14]

It is necessary to determine whether a given simulation actually measures the performance parameters it is supposed to measure. The simulator should reveal the difference in skills between experienced surgeons and beginners. This issue was addressed in recent studies of simulators for laparoscopy[15] and arthroscopy,[16] in which the experienced surgeons performed significantly better than the novices. Another study demonstrated that the simulator was able to assess the psychomotor skills in residents.[17]

Experience with ophthalmic virtual reality simulators is limited. Previously, an eye surgery simulator was presented,[18] and more recently, a vitreous surgery simulator[19] and an intraocular surgery workstation using a mechanical eye model.[20] The educational value of virtual reality applications for eye surgery has still to be demonstrated and must be compared with currently used training methods. These studies will put the spotlight on what constitutes good surgical skills and how these should be measured objectively. Next, the validity of the phacoemulsification simulator will be tested in a study comparing the results of experienced cataract surgeons, residents in ophthalmology, and medical students. The computer will perform objective measurements of variables such as phacoemulsification time, distance covered by the phacoemulsification tip inside the eye, and number of inappropriate or dangerous movements performed with the phacoemulsification tip. The educational value should be verified by comparing the learning curves in 2 groups of novices, namely, those who have and those have not undergone simulator training.

In conclusion, we believe that in the near future virtual reality surgery will be an important supplement to what is currently considered the best training approach to learn phacoemulsification. Our pilot study on medical students indicates the importance of the teacher being present with the novice during the exercises. Ultimately, the value of simulators will be measured by their ability to improve patient outcomes.

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