

REVIEW

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A Systematic Review of Phacoemulsification Cataract Surgery in Virtual Reality Simulators

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Summary. *The aim of this study was to review the capability of virtual reality simulators in the application of phacoemulsification cataract surgery training. Our review included the scientific publications on cataract surgery simulators that had been developed by different groups of researchers along with commercialized surgical training products, such as EYESI® and PhacoVision®. The review covers the simulation of the main cataract surgery procedures, i.e., corneal incision, capsulorrhexis, phacosculpting, and intraocular lens implantation in various virtual reality surgery simulators. Haptics realism and visual realism of the procedures are the main elements in imitating the actual surgical environment.*

The involvement of ophthalmology in research on virtual reality since the early 1990s has made a great impact on the development of surgical simulators. Most of the latest cataract surgery training systems are able to offer high fidelity in visual feedback and haptics feedback, but visual realism, such as the rotational movements of an eyeball with response to the force applied by surgical instruments, is still lacking in some of them. The assessment of the surgical tasks carried out on the simulators showed a significant difference in the performance before and after the training.

Introduction

The master-apprentice teaching method has been commonly used in the medical education since it is the best approach to transfer the surgical skills from a professional surgeon to a medical practitioner. Microsurgery is one of the easy surgeries to be learned, but hard to be mastered. It involves the ability of surgeons to withstand the psychological pressure during the surgery procedures, which affects their performance (1). Junior surgeons usually encounter this problem since they lack actual surgical experience and strong mind. This may be caused by the limited number of surgical study samples and equipment provided for surgical training during their studies since the number of medical scholars has been growing multifold in the past 10 years (2).

The successful implementation of the training simulator in the aviation academy has triggered interest among researchers to shift this idea and technology into the medical field. With the invention of a force feedback haptic device, a virtual reality surgery simulator is becoming a hot future prospect, which is capable of providing an alternative way in surgical training besides the experimentation on human dummies and animal cadavers (3). Current technology on the central processing unit (CPU) and graphics-processing unit (GPU) is well

suited for the precise 3D human body modeling. A further improvement in the degree of realism of human tissues rendered in the surgery simulator will be the best evidence for researchers to convince professional surgeons to apply the simulator in the surgical training system.

Cataract is categorized as a common vision illness, which is diagnosed in a large group of eye patients every year. The majority of such patients are affected by this illness due to aging (4) or overexposure to ultraviolet light. Cataract is the clouding of the lens, which is situated behind the iris and the pupil. The reduction in clarity of the lens prohibits the penetration of light from entering into the retina, thus, reducing the vision seriously. An ophthalmologist with a good mastery of cataract surgery is required during a surgical operation of cataract since any mistake may cause surgical trauma, which leads to permanent blindness or prolongs the recovery of a patient. The implementation of the virtual reality surgery simulator can be incorporated in cataract surgery since it can generate the physical details of the patient's eye by using the data provided by CT and MRI scans (5). Therefore, surgical rehearsal and training can be carried out using the simulator, and it is especially beneficial for junior inexperienced ophthalmologists.

The paper is organized as follows: first, the history and evolution of cataract surgery are addressed; then, there is a review on the implementation of 4

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main phacoemulsification cataract procedures, i.e., corneal incision, capsulorrhexis, phacosculpting, and intraocular lens (IOL) implantation, in a range of surgical simulators; later, different simulators are discussed and the conclusions are drawn from this review.

Phacoemulsification Cataract Surgery

During the first 40 years of the 20th century, cataract surgery was conducted by using intracapsular cataract extraction (ICCE), which was the predominant form of lens removal at that time (6). However, patients were forced to endure long hospitalization with full head immobilization. A large corneal scleral incision made to remove the entire capsule and the nucleus from the eye might possibly lead to postoperative complications, such as vitreous loss and retinal detachment (7).

After the introduction of an IOL and an improvement in operating microscopes in the 1950s, extracapsular cataract extraction (ECCE) was widely employed in cataract surgery (8). It involved a smaller incision compared with ICCE and an intact posterior capsule or supporting IOL left behind after the extraction. But the occurrence of a postoperative inflammation and dense posterior capsule opacification (PCO) was hampering ECCE for a decade before improvements were made in automated irrigation-aspiration systems and capsulotomy techniques (7).

Phacoemulsification, which was adopted widely in cataract surgery, was developed by Dr. Kelman in 1967 (9). His idea of fragmenting and removing cataract from the eye through a very small incision was inspired by an ultrasonic probe that was used by his dentist to clean the teeth. One of the major advantages of this technique is that a small incision is usually self-sealing, which shortens a recovery period efficiently. Intraocular pressure (IOP) can be maintained at a normal range throughout the operation with the modern technology of fluid dynamics in the phacoemulsification machine.

The phacoemulsification cataract surgery usually begins with topical anesthesia by the instillation of a few proparacaine drops on the ocular surface. It is a safer and more efficient technique compared with retrobulbar anesthesia, where a long needle is inserted through the lower eyelid to anesthetize the area behind the eyeball (10). After that, an ophthalmologist makes an incision of about 2.8 mm at the temporal limbus to allow the insertion of surgical instruments. The anterior surface of the capsule that encloses the nucleus is removed then, and the procedure is called capsulorrhexis. A phaco hand-piece with a steel needle vibrates at an ultrasonic frequency to emulsify the cataract into small pieces, while the aspiration port at the tip of the probe removes the fragments by suction from the pump.

The cataract surgery is considered complete when a foldable silicon or acrylic IOL of appropriate power is implanted into the capsular bag, and a few or no stitches are required since the incision is small.

Fig. 1 shows the images captured from the video of a phacoemulsification cataract surgery. The lid retractor is used in the surgery to support the upper and lower eyelids in order to expose a large surface of the eyeball for ophthalmologists to perform the surgical procedures easily. Besides that, it also prevents the eye blinks during the operation to avoid misposition of the surgical instrument, which can lead to a serious injury. As it can be seen from Fig. 1, the eyeball moved according to the direction of the external force applied by the surgical instruments.

Simulation of Phacoemulsification Cataract Surgery

As it can be seen, the traditional apprentice model applied in surgical training entails patient flows, financial costs, and human costs. Numerous simulators for phacoemulsification cataract surgery have been developed in the last 20 years with the intention to provide a virtual surgical training platform that can expose ophthalmologists to the different types of surgical challenges and complications without the need to consider the risk involved and patient safety. The earliest research was started during the 1990s (11), when the processing power of the computers and the performance of graphics hardware were still limited. The main procedures of the surgery, such as corneal incision, capsulorrhexis, nucleus extraction, and IOL insertion, are embedded in the simulator for ophthalmologists to enhance their expertise in these specific areas.

Corneal Incision

The size of the incision has been reduced to minimal in modern cataract surgery. The ideal incision for phacoemulsification cataract surgery should be astigmatically neutral and free of sutures (12). A scleral tunnel incision and a clear corneal incision differ in position, shape, and size. The scleral tunnel incision is fashioned with a 5.5-mm scleral groove 1 mm behind the limbus. A backward cut of 1–1.5 mm, radial to the limbus, is made from each edge of the incision followed by a scleral tunnel with a crescent knife that extends approximately 2–2.5 mm into the cornea (13). The scleral incision may be preferable on patients with low preoperative corneal endothelial cell counts, but greater operation time is necessary and suturing of the wound is strongly required to prevent leakage with pressure.

The clear corneal incision, which is positioned anterior to the limbal vascular arcade, is more commonly used by ophthalmologists due to its self-sealing ability and the implementation of a foldable IOL (14). The size of the incision, with the standard being

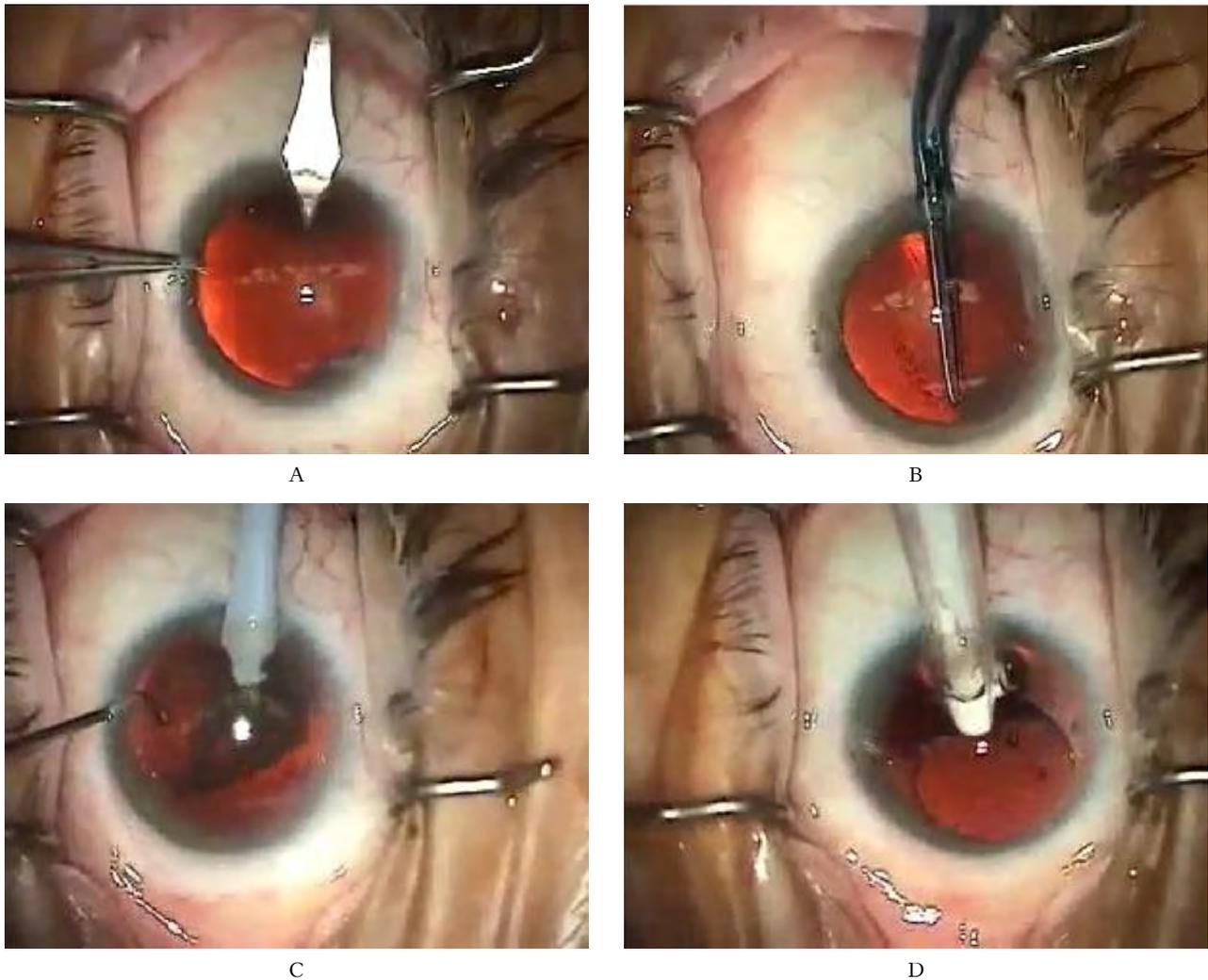


Fig. 1. Phacoemulsification cataract surgery
A, corneal incision; B, capsulorrhexis; C, phacosculpting; D, IOL implantation.

about 2.8 mm wide with the options down to 2 mm and even smaller, normally depends on the size of a phaco probe. Various studies have shown that the clear corneal incision is capable of reducing astigmatism during the cataract surgery effectively and beneficially for patients with a filtering bleb or coagulation disorders. The corneal tunnel simulation firstly developed by Agus et al. (15) did not support the direct interaction between the tool and the eye. The incision is modeled as a circular arc by a geometric tool that provides the selection of the corneal insertion point and the tunnel geometric features, such as orientation and width. A partial reorientation of the incision and cut enlargement are then performed in the cutting stage by constant computation.

El-Far et al. (16) constructed the test models that are composed of triangular meshes as the surface of the eye model in their telementoring cataract surgery application. They evaluated a set of test cases in an effort to modify the topology by deleting and separating the triangles that are in contact with the

cutting edge of the keratome. The area around the incision point on the cornea is highlighted to draw the user's attention. The technique of a clear corneal incision accompanied by paracentesis in modern cataract surgery was introduced in the medical education simulator invented by Perez et al. (17) as shown in Fig. 2. The instruments, such as a spatula or a hook, can be inserted through the side port during the simulation to for subsequent procedures.

Choi et al. published an article detailing a surface mesh cutting that is developed as a clear corneal incision in a virtual training simulator. The triangulated surface meshes are cut interactively in response to the user's action. The triangles along the cut path sampled from mesh-tool interactions are subdivided to form the shape of the opening. Subsequently, a pair of adjacent triangles merges to form a single triangle to avoid the creation of tiny elements that consume processing power. Visual guides are superimposed on the eye model to suggest the optimum positions of grasping and incision (18).

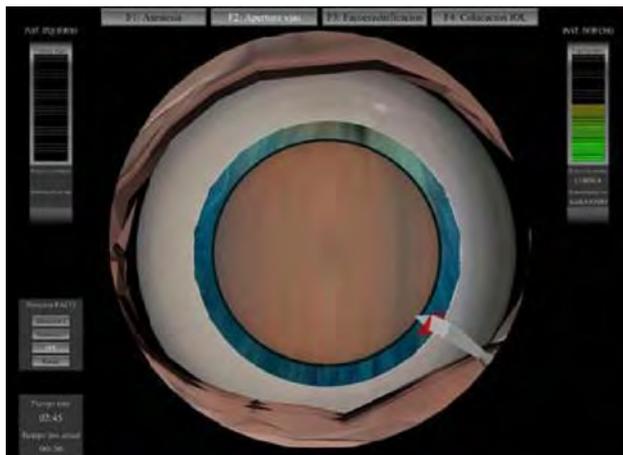


Fig. 2. Cornea incision by using virtual keratome
Adopted from Perez et al. (17)

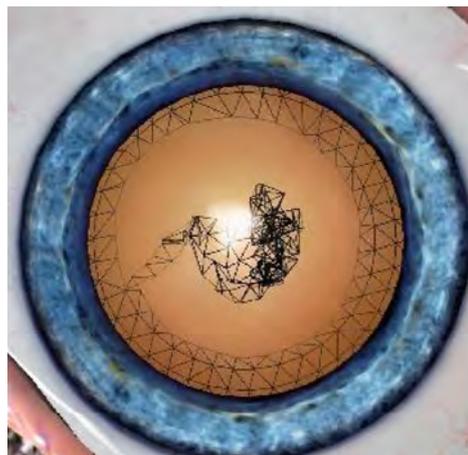


Fig. 3. Continuous curvilinear capsulorhexis simulation
Adopted from Weber et al. (22)

Capsulorrhexis

Continuous curvilinear capsulorrhexis (CCC), which provides ophthalmologists with an intact capsular bag for IOL implantation, was introduced by Gimbel and Neuhann in the middle of the 1980s (19). This method begins with initial radial and circumferential cuts in the capsule to create an anterior capsular flap. Pande (20) proposed that viscoelastic materials be injected under the capsular flap to raise the V-shaped tear created by the cuts. Forceps are normally used to tear the anterior capsule spirally by grasping and pulling the capsular flap. The raised flap has to be pulled gently and carefully with the force directing to the center of the eye in order to achieve a smooth-edged continuous curvilinear opening.

Agus et al. (15) geometrically modeled the anterior capsule as a mesh composed of triangular facets. A mass-spring network is implemented into the mesh for physical simulation where mass particles are mapped over the mesh vertices, and liner springs are mapped over the mesh edges. Virtual forceps are designed to be controlled by a haptic device to move the particles of the mesh to imitate the action of breaking the anterior capsule. The simulation of CCC by Choi et al. (18) introduced a progressive cutting method to represent the tearing process. This is done by determining the cut points due to tearing obtained from the linear combination of the cut segment vector and the projected force vector exerted on the flap. The new cut point will only be sampled when the force exceeds a present threshold force of tearing. Red lines are applied on the anterior capsule to indicate the correct direction of turning the flap by maneuvering the virtual cystotome.

Webster et al. (21) demonstrated the simulation of the CCC technique in a haptic surgical simulator and the EYESI[®] system. The capsular tissue is modeled as a curvilinear mesh of nodes and springs

in the system. They implemented a modified hybrid mass-spring model, which has an advantage in the computational speed and simplicity to accomplish the deformation. The direction of the tear based on the force vectors acting on the mesh is determined by using a heuristic algorithm. The simulator alerts the user to any potential surgical complications before they occur. It is very useful as a teaching tool, especially for instructing novice ophthalmologists. Weber et al. (22) found that the tearing of the membrane can be simulated realistically by combining an algorithm for descriptive tear propagation with an algorithm for interactive cutting. They divided the tearing action performed in capsulorrhexis into 2 different techniques: shearing and ripping. Whereas shearing only enables small-sized deviations from the current tear direction, ripping enables relatively abrupt changes in tear propagation. A parameter called an indicator is used in the system to determine and initiate the 2 techniques via observation of the normal of the triangles that are adjacent to the tear end and detached membrane patch. The planning of ripping maneuvers for the rescue of an errant capsulorrhexis tear can be learned from this implementation (23). Fig. 3 illustrates the simulation of CCC developed by Weber and colleagues.

Phacosculpting

Phacoemulsification cataract surgery has become one of the most successful and safest surgeries after the refinements on the ultrasonic probe and the phacoemulsification machine. Various types of techniques have evolved to extract the nucleus with ultrasonic energy after the introduction of phacoemulsification by Dr. Kelman. The divide and conquer nucleotomy is the most popular method of emulsification, which involves breaking the nucleus into quadratic sections (24). This technique gener-

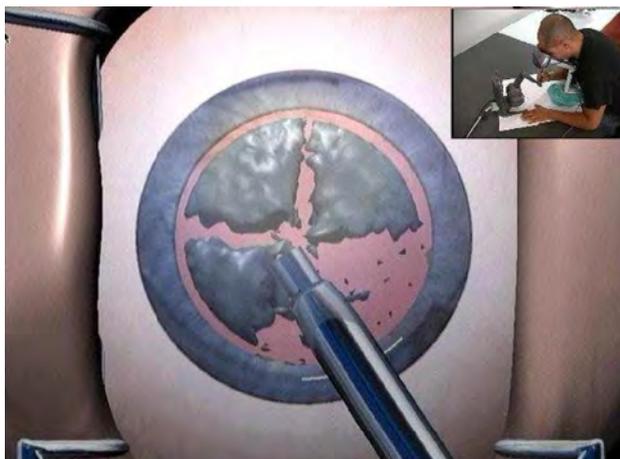


Fig. 4. Virtual phacoemulsification training
Adopted from Agus et al. (15)

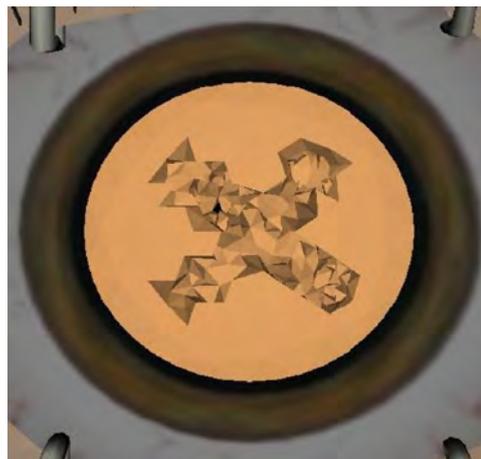


Fig. 5. Cross-shape trench created by using the divide and conquer technique
Adopted from Choi (26).

ally incorporates 4 basic steps and begins with the deep sculpting of the nucleus until a very thin posterior plate of the nucleus remains. The next step is fracturing the nuclear rim and the posterior plate of the nucleus with lateral pressure by using a probe and a spatula. The same step is repeated after rotating the nucleus by 90° to break away a wedge-shaped section of the nucleus for emulsification. The procedure is finished by emulsifying each quadratic section in a systematic manner. Crater divide and conquer, trench divide and conquer, phaco chop, and stop and chop are the types of phacosculpting techniques performed by ophthalmologists depending on the hardness of the nucleus and individual cataract case.

Agus et al. (15) modeled the nucleus as a collection of simplices that were built from a tetrahedron mesh with mass particles placed inside the tetrahedron barycenters. A Russian roulette scheme was employed to keep into account the ultrasound effect and the nucleus hardness. They used a shape-matching approach for dynamic simulation to eliminate the overshooting problem of explicit integration schemes. The energies by geometric constraints and forces were replaced by the distances from the current positions to the goal positions. The training system consisted of a virtual phacoemulsificator as shown in Fig. 4 to perform phacoemulsification simulation.

The erosion and absorption of the lens in the cataract surgery simulator, which Barea et al. (25) developed, are simulated by applying Gaussian properties in the H3D programming language. The erosion power of the phaco probe is studied in the system by controlling the size of the crystalline lens destroyed and absorbed during the procedure. The research on the representation of anterior chamber structures with finite element models has been undertaken by Barea et al. to realize the static and

dynamic structural analysis on the distortions. The system is able to educate the user about the estimated maximum pressure that can be applied on the eye model without exceeding the limits of rupture.

The clouded lens model in the virtual training simulator reported by Choi (26) is built by generating a triangulated surface mesh accompanied by the application of Delaunay tetrahedralization to yield a tetrahedral volumetric mesh. The mesh is updated interactively by deleting the tetrahedrons sculpted away using the tip of the virtual phaco probe to simulate the visual effect of phacoemulsification. Bounding boxes arranged with a hierarchical octree are used to construct the collision detection system, where the boxes at the lowest level of the hierarchy are bounded to the tetrahedrons. Four neighbors are registered for each tetrahedron to reduce the time required to identify the subsequent collision. The phaco probe in the simulator is modeled as a bounding sphere, and the tetrahedrons of the lens are removed when the distance is shorter than the radius of the bounding sphere. The system will only render the outermost tetrahedrons that are exposed on the surface to enhance the real-time performance as shown in Fig. 5. In addition, the nucleus rotation in the capsular bag with a response to the inertia during phacosculpting has been implemented by a group of researchers to improve the visual realism of their simulator for cataract surgery.

Söderberg et al. have published articles addressing computer-simulated phacoemulsification in a simulator named PhacoVision[®], which has been developed based on M-base[®] and working on top of Cosmo 3D/Optimizer (27). The trainee input interface of the simulator consists of a phaco handpiece and a nuclear manipulator handpiece, which are used during phacosculpting. With the intention of imitating the actual environment of cataract surgery, a microscope foot pedal and a phacoemulsifi-

cation pedal are equipped to control the view of the surgical field and the modes of the phaco machine, respectively (28). The hardness of the nucleus can be altered in the system freely, by controlling the rotation of the nucleus and the movements of the pieces of the nucleus due to aspiration. The surgical event in the phacoemulsification module, such as air bubble generation from irrigation holes, is implemented to increase the difficulty of virtual reality training.

IOL Implantation

An intact posterior capsule is left behind after phacoemulsification to provide support for an IOL, which replaces the clouded crystalline lens to focus a sharp image on the retina. Previously, a polymethylmethacrylate (PMMA) lens was used due to its nontoxic characteristic, but it has been superseded by the use of a foldable lens that only requires a smaller incision for implantation. The designs of foldable IOLs can be single-piece, three-piece, or plate haptic lenses and are usually made of silicon, soft acrylic, or hydrogel. An acrylic lens is most commonly used because it possesses a higher refractive index and preserves most of the advantages of the physical properties of the PMMA lens (29). Specially designed forceps or an injector is used as an insertion device for IOL implantation. Refractive power correction, which is incorporated in the recent invention of a multifocal IOL, allows the focusing of both distant and near images on the retina (30). Therefore, patients can benefit from restoring their vision significantly without the aid of spectacles after cataract surgery.

Perez et al. (17) included IOL implantation as one of the training procedures of cataract surgery in their simulator. A lens injector and a hook as illustrated in Fig. 6 are designed virtually to replicate the actual process. Ophthalmologists are able to carry out their training by employing the techniques of inserting an IOL and positioning its haptics into the capsular bag precisely.

Discussion

As it can be seen from the review, the various types of cataract surgery simulators that have been developed by different groups of researchers are able to provide a suitable training platform for ophthalmologists to master the surgical techniques without any risk to the patients' eyes. The training application developed by Shen et al. (31) is a real-time telesurgery simulation. The telementoring guidance is similar to the traditional master-apprentice model, but a junior ophthalmologist or a medical practitioner is led by a remote expert through the CANARIE network (32). Data on the position and force are recorded from the haptic device that is controlled by the expert and transferred to the student's

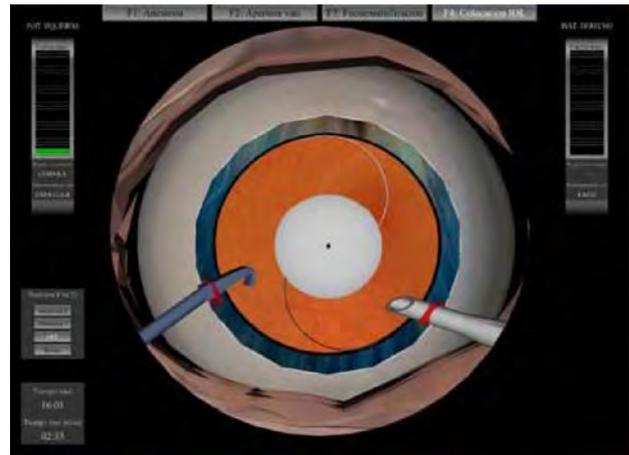


Fig. 6. IOL implantation
Adopted from Perez et al. (17)

haptic device as a way of teaching the proper motion to the student. To demonstrate this type of teaching and learning method, a research team has invited a group of eye surgeons and students for the analysis of haptics realism, graphics realism, and usability, and the feedback received from the participants is positive (33). It is believed that in the coming years, the transfer of skills from experts in one country to surgeons from other country can further be expanded and achieved effectively over long distances.

Choi et al. (18) have introduced a quantitative measurement system in their simulator to evaluate the user performance during cataract surgery training. The measurement of the distance from the optimal grasping location, the angle and size of insertion, and the penetration depth are collected to assess the dexterity of users in performing the corneal incision. The performance of the virtual CCC training can be evaluated by referring to the location of the puncture made on the anterior capsule and the size of the cut and the trajectory of cystotome-capsule contacts. The completion time, the number of tetrahedrons removed, the trench width and depth, and the crossing angle are recorded to analyze the phacosculpting process. The data collected from the training of the 3 surgical procedures are illustrated in a set of graphs and converted into the generic XML format for trainees to conduct further investigation in order to improve their skills.

PhacoVision®, which was invented by Söderberg and his team, simulates the cataract surgery procedure realistically with interactive hardware interfaces. A performance index is implemented into the simulator to monitor the skill in a virtual reality phacoemulsification surgery (34). The evaluation system is divided into 2 phases: the sculpting phase and the evacuation phase. The valid variables for the sculpting phase are the total procedure time,

the sculpting time, phaco energy used, the manipulator behind the iris time, the phaco rhexis damage time, and the manipulator beyond the posterior capsule time. Where phaco energy is used, the irrigation time, the iris damage time, and the phaco beyond the posterior capsule time are identified as valid variables in the evacuation phase. A study of the performance index was conducted on 2 populations formed by individuals unfamiliar with cataract surgery and experienced ophthalmologists, respectively. The results showed that the system was useful in analyzing the performance of the users (35).

EYESI[®] from VRmagic GmbH, as shown in Fig. 7, is one of the well-developed simulators available in the market currently (36). The device replicates the actual environment of cataract surgery with a cataract eye interface, a cataract instrument set, and foot pedals. In addition, the view through a microscope from the platform is similar to the actual surgical microscope. A number of articles have been published detailing the results of the training and assessment on EYESI[®] by users with different levels of experience in ophthalmology. Different types of training modules are being implemented into the surgical simulator along with the statistical analysis on the performance (37–40). The outcome of the studies shows that the experience obtained from virtual reality training allows improving the precision and the dexterity of surgical techniques effectively and efficiently.

Concluding Remarks

The involvement of ophthalmology in the virtual reality research for over 20 years since the early 1990s has made a great impact on the development of surgical simulators. Most of the latest cataract surgery training systems are able to offer high fidelity in visual feedback and haptics feedback, but visual realism such as the rotational movements of an eyeball with a response to the force applied by surgical instruments is still lacking in some of them. The assessment of the surgical tasks carried out on the simulators showed a significant differ-



Fig. 7. EYESI[®]

Adopted from VRmagic GmbH

ence in the performance before and after the training. Unfortunately, the recent survey has reported that virtual reality simulation is recognized as an unfamiliar training and assessment tool within the realm of academic ophthalmology (41). This may be due to the cost of a commercial simulator such as EYESI[®], which is priced more than \$100 000 on the average (42).

Statement of Conflicts of Interest

The authors state no conflict of interest.

Acknowledgments

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