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Virtual Reality in Ophthalmology Training

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Abstract. Current training models are limited by an unstructured curriculum, financial costs, human costs, and time constraints. With the newly mandated resident surgical competency, training programs are struggling to find viable methods of assessing and documenting the surgical skills of trainees. Virtual-reality technologies have been used for decades in flight simulation to train and assess competency, and there has been a recent push in surgical specialties to incorporate virtual-reality simulation into residency programs. These efforts have culminated in an FDA-approved carotid stenting simulator. What role virtual reality will play in the evolution of ophthalmology surgical curriculum is uncertain. The current apprentice system has served the art of surgery for over 100 years, and we foresee virtual reality working synergistically with our current curriculum modalities to streamline and enhance the resident's learning experience. (**Surv Ophthalmol 51**:259–273, 2006. © 2006 Elsevier Inc. All rights reserved.)

Key words. resident competencies • simulation • skill acquisition • surgical curriculum • virtual reality

Historical Perspective

A growing interest in the potential for simulation to affect patient safety and improve the quality of medical education and training surfaced in the 1990s, and research teams throughout the USA initiated the concept of surgeons rehearsing procedures via computer simulation. The first surgical simulators appeared on the scene with a lower extremity surgery model in 1990[23] and an abdominal surgery simulator in 1993.[78] Eye surgery simulation was not long to follow with a retrobulbar injection simulator in 1992[59] and an ophthalmic surgery simulator in 1993.[44] In the last decade advancements in computer capabilities have combined with technological breakthroughs in virtual reality to produce a shift from crude experimental virtual-reality designs to commercial viability in surgical simulation. The culmination of these efforts came to fruition in 2004 when the FDA voted to make virtual-reality simulation of carotid stent placement an important component of training,[27] thus establishing virtual reality as a cornerstone of future procedural training.

The concept of simulation was born in 1929 when Edward Link developed a mechanical flight simulator to reduce the incidence of catastrophic accidents in flight. Computer-generated simulation was first

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introduced in 1963 in a landmark doctoral thesis by Sutherland on man–machine graphical communication systems which galvanized the research community and set the tone for future technological breakthroughs. In 1989 Jaron Lanier and the private sector bestowed the term *virtual reality* on the evolving field of computer-based simulation.

In the 1970s and 1980s the United States military invested heavily and was the driving force behind the development of virtual-reality trainers. The concept of virtual-reality training is vital to military and private aviation pilots and crews (Fig. 1). In the military, many more hours are spent "flying" simulators than real aircraft, and almost every weapon and vehicle in the Army and Marine Corps armamentaria today has simulation built into it.[2,53]

Definition

Virtual reality can be broadly defined as the use of computational methods to propel users into a multimedia environment that simulates reality. Through the combination of human–computer interfaces, graphics, artificial intelligence, haptic (touch and pressure feedback) technology, high-end computing, and networking, current virtual-reality systems allow the user to become immersed in and interact with an artificial environment. There are four essential components in any virtual-reality simulator: a virtual world, immersion, sensory feedback, and interactivity.[84]

The virtual world is the description of objects within the simulation through software programming. Immersion is the sensation or experience of physically and, hopefully, mentally being in the virtual world through synthetic visual, haptic, and/or auditory stimuli. Sensory feedback is an essential ingredient of any virtual-reality simulation. Visual feedback is considered standard, but haptic feedback is an integral component of surgical simulation. Finally, interactivity means that the actions of the user should have a direct effect on the virtual world in which the user is engaged.

Fig. 1. Flight simulation is a standard part of pilot training today. Shown here is the DASH8 flight simulator developed by 3D Perception, Inc. (Photo courtesy of 3D Perception, Norway.)

Virtual-reality simulation can be divided into three levels of complexity.[88] Simplified virtual reality is limited to a computer–user interface that does not use real-world props, artificial intelligence, or supporting systems. The most widely used medical example of simplified virtual reality is anatomic atlases.[85] Advanced virtual reality involves visual and haptic computer–user interface, most often derived from the use of external props. Early surgical simulation was a mixture of advanced virtual-reality systems in which haptic feedback was lacking. Immersive virtual reality requires sensory input and output incorporated through haptic instruments. Artificial intelligence capabilities provide cognitive interaction and assessment. Using current virtual-reality technology, the learner becomes not merely a passive observer of pictures in a text but can actively modify a 3-D virtual world.[26]

Current Ophthalmology Training Concepts

In 2000 the Institute of Medicine published a report entitled "To Err is Human," which placed the burden of medical mistakes at a mortality rate between 44,000 to 98,000 per year in the USA. In essence more people die from medical mistakes than from highway accidents, breast cancer, or AIDS.[48] Much publicized, the report spurred a tremendous outcry from the public and this sentiment was echoed by the Joint Commission on Accreditation of Healthcare Organizations (JCAHO), the National Committee for Quality Assurance (NCQA), and other organizations who called on the medical profession to protect the public. Attention turned to the means by which physicians earn licensure and in 2001 the Accreditation Council for Graduate Medical Education (ACGME) established six general competencies for resident education: medical knowledge, patient care, practice-based learning, interpersonal and communication skills, professionalism, and systems-based practice. The American Board of Ophthalmology (ABO) added a surgery as a seventh competency to the list.

Unfortunately, neither the ACGME nor the ABO has delineated the exact mechanisms and models by which these competencies are to be evaluated; furthermore, ophthalmology training programs are expected to be in compliance by 2011. The literature on ophthalmology education has expanded since the new competencies were introduced. [32,51,52,61,64] Currently, 90 degree evaluation forms, surgical logs, and incident reports are used in the evaluation of surgical competency; Lee and Carter suggest a direct observation checklist of performance and video review and critique with faculty surgeon of intraoperative complications as methods of evaluating surgical competency.[51] But a method to objectively and quantitatively assess surgical competency is needed.

It is currently estimated that medical knowledge and techniques double every 6 to 8 years,[47] and such an onslaught of information must be matched with an innovative teaching medium capable of providing efficient, self-directed instruction in an adult learning environment. In addition, the new wave of minimal access surgery requires a dexterity that does not lend itself to be learned via observation alone. The Halstedian apprentice model of teaching has served ophthalmology education and been the standard mode of surgical instruction for over 100 years,[37] and "see one, do one, teach one" has been the quintessential slogan of the medical education system. Current trends in surgical technique necessitate a more malleable and durable training format than the apprentice method. We are in need of a teaching medium that will meet the challenges of the coming surgical breakthroughs. The limitations[87] of the current educational approach are quite difficult to ignore, are even more difficult to amend, and include the following: unstructured curriculum, financial costs, human costs, and time constraints.

Learning by doing provides skill acquisition in the framework of an unstructured curriculum, failing to ensure that experience is gained in all of the vital areas. Without due attention, systematic instruction may be lacking and important concepts may be neglected. Under the apprentice model, the curriculum is dictated by patient flow, and in a given three-year period certain surgical situations might present too infrequently.

The financial costs of teaching in the current state of medical care are astronomical. Increasing demands on health care, departmental budget constraints, and heightened sensitivity to medical–legal considerations are all financial factors that limit resident instruction and impinge on valuable experience in the operating room. The ACGME requirements for resident work hours, teaching, and evaluation are putting additional stressors on training program budgets. The national annual cost of training surgical residents of all specialties in the operating room alone was extrapolated by Bridges et al to be US$ 53 million.[12]

The human cost of the apprentice approach is also an issue to be considered. Virtual-reality simulation is innocuous to the patient during the period of skill acquisition and, when implemented in conjunction with current training methods, holds the promise of possibly reducing patient morbidity through an improved training experience.[66,67]

Time constraints leave very little to spare for educational purposes. An efficient, systematic approach is direly needed to work in conjunction and synergize with the current training model.

Indeed, academic ophthalmology has supplemented the apprentice model with mannequins[56] and with microsurgical skill or wet lab experiences. In the Winter 2005 *ACGME-RRC News for Ophthalmology*, wet labs were introduced as a new requirement for the surgical competency component of the ACGME mandate. In the microsurgical skill lab, ophthalmologists in training practice their surgical skills on animal or cadaveric tissues. Wet labs provide a training environment that allows for repetitive practice of technique without risk to the patient; they also provide important tactile feedback that can only be simulated by manipulating real living tissue.

Wet-lab experiences are effective in modeling surgical technique, but they are limited in their availability partly as a result of their financial cost.[66] Not all residency programs in the USA had the capacity for wet-lab training when the microsurgical skill lab requirement was introduced; all are clamoring to develop a wet-lab curriculum. In a recent survey of ophthalmology senior house officers in the United Kingdom, it was found that 40% had access to wet labs and 39% had spent time in a wet lab in the previous 6 months.[31] Virtual-reality simulation entails a large investment initially, and currently is not a better financial alternative to wet labs. But with improving technologies and a more embracing market, virtual reality will become more and more affordable.

Virtual-reality trainers could be used to deliver a more broad-based, systematic, and efficient training curriculum; in addition, virtual-reality trainers are available at any time for all residents to practice difficult procedures repeatedly.[77] Some have projected that virtual-reality simulators might shorten residency programs and lower educational costs.[65] It appears that virtual-reality simulators are a logical solution for the troubling obstacles that face the surgical education system. There exists no doubt that optimism is warranted when discussing the potential of virtual reality in surgical training. The exact role of virtual-reality simulation is yet to be defined, but most agree that it will at least be an educational format complementary to the basic educational tools already in use.

Virtual Reality in Surgical Training

DISCIPLINES

Nearly all branches of surgery, including general surgery,[58,76] urology,[41,45,82] neurosurgery,[88] obstetrics and gynecology,[55] otolaryngology,[79] and orthopedic surgery,[91] have embraced virtual reality training in one form or another. In addition, anesthesiology[40,75] and medicine subspecialties that are procedure-oriented, such as gastroenterology, pulmonology,[19] and cardiology,[21] have also entered the arena of virtual reality. Training systems have spanned everything from endoscopic sinus surgery[79] to laparascopic gynecological surgery[33] and beyond.[10,75]

At the moment it would be bold to claim that virtual reality is the educational convention in surgical education, but at the same time it is unreasonable to discount the many signs that virtual reality technology is slowly gaining acceptance in surgical training programs. Virtual reality will be a standard component of surgical training in the years to come, but when and to what extent are still to be seen.

TRIALS

The pressing question is whether or not virtual reality simulation works to enhance the learning of surgical techniques. Flight simulation has dramatically improved the quality of training pilots receive. Knowledge transfer in surgical trainers was approximately 25–28% in 1998, far short of the 50% attained in flight simulators.[80] With the constant flux of new technologies, simulation packages and applications are in continuous improvement; more importantly, there is an endless need to prove the efficacy and extent of knowledge transfer in these newer systems. For this reason not all research on virtual reality simulators has yielded reassuring results;[4,25] the findings of individual trials speak primarily to the virtual reality trainer tested specifically and not to virtual reality trainers in general. Trials of surgical virtual reality simulators can be loosely divided into those that aim to show skill acquisition, those that aim to show a virtual reality system as a valid discriminator of surgical proficiency, and those that aim to show the impact of virtual reality (VR) on operating room (OR) performance, so-called "VR to OR". The gold standard in trials is VR to OR.

SKILL ACQUISITION TRIALS

Skill acquisition trials on an ureteroscopic simulator[45] and a laparoscopic simulator, the MIST,[69] have shown improvement in skills with repetition of virtual reality surgery as measured by the virtual reality simulator. Research by Ali et al indicates that more challenging laparascopic cholecystectomy virtual reality simulation results in more improvement over time and better final skill level when compared to less difficult simulation.[3]

ABILITY-TO-DISCRIMINATE TRIALS

Ability-to-discriminate trials span the spectrum of virtual reality simulation with respect to field of application and complexity of the virtual world. A flexible sigmoidoscopy virtual reality simulator was found an effective discriminator of operator experience, with more experienced groups displaying a better efficiency ratio and duration of procedure.[20] A study of a transuretheral prostate resection trainer found that the expert group spent less time with orientation, resected more total tissue, had more volume resected per cut, and performed fewer errors.[90] Another trial on a bronchoscopy simulator showed that experts visualized a greater percentage of segments, had fewer wall collisions, and had a better economy of performance.[63] Similar reports exist validating a flexible cystoscopy simulator,[82] an upper gastrointestinal endoscopy simulator,[11,62] and laparascopic simulation (Procedicus MIST-VR)[14,28,34] (Fig. 2) as discriminators.

VR TO OR

Virtual reality to operating room trials are limited to studies done on the MIST-VR system which is a low fidelity simulator. Seymour et al in a randomized, blinded study showed that residents trained on the MIST-VR performed 29% faster gallbladder resections while non-virtual reality trained residents were 9 times more likely to transiently fail to make progress and 6 times more likely to make errors.[81] In the study reported by Grantcharov et al, operating room performance was assessed before and after randomization to virtual reality–trained and non-virtual reality–trained groups. The virtual reality–trained residents performed the laparoscopic cholecystectomy faster, with greater improvement of error, and with a better economy of movement scores.[35]

Results of trials show knowledge transfer of skills through virtual reality to be improving from the 25% to 28% estimated by Satava in 1998.[80] There is an outcry of support for objective assessment of clinical skills around the world.[6] It is evident that the potential of virtual reality simulation in surgical training is quite extraordinary despite the lack of widespread institutionalization in surgical training programs.

Fig. 2. The Procedicus MIST trainer simulates laparoscopic surgical techniques through visual and haptic interfaces. (Photo courtesy of Mentice, Gothenburg, Sweden.)

APPROVED SYSTEM

In a sign that virtual reality simulation is making a transition to the mainstream, an FDA panel voted in August 2004 to make virtual-reality simulation of carotid stent placement an important component of training. In the same month the Society for Cardiovascular Angiography and Interventions, the Society for Vascular Medicine and Biology, and the Society for Vascular Surgery all publicly endorsed the use of virtual reality simulation in carotid stent training. This seminal event in the history of surgical virtual reality marks the beginning of a new era in training approach.[27] To our knowledge there is no other virtual reality application approved for procedural training in the USA or in any other country.

Virtual Reality in Ophthalmology Training

CURRENT TRENDS

Today, the apprentice model carries with it the realities of an unstructured curriculum dependent upon patient flow, heavy financial costs, human costs, and unmanageable time constraints. Unfortunately, ophthalmology may be even more vulnerable to the flaws of the apprentice approach because of its dependence on microsurgical technique and its constant influx of new technology. The number of skills to be mastered has increased at a near exponential rate in complexity and multitude. Reciprocally, this demand for complex skill acquisition has been met by decreasing clinical loads and surgical cases. With the current pressure of the surgical competency requirement laid down by the ABO, ophthalmology education is in need of a quantitative method of assessing resident surgical skills. More importantly, we are in need of an instructional medium that will reduce surgical risk to patients, expose surgeons to surgical experience and complications, and carry our training programs through the 21st century.

Having recognized these limitations in the apprentice method and citing the increasing demand for surgical simulation, researchers have developed many ophthalmic virtual reality surgery simulators (Table 1).[39] The training systems published in the literature come from the USA, Japan, France, Sweden, and Germany and include retrobulbar injection,[59] capsulorhexis,[94,95] cataract extraction via phacoemulsification (Figs. 3 and 4),[50,86] retinal photocoagulation,[74] and vitreoretinal surgery (Figs. 5 and 6).[39,46,73,92]

In 1993 and 1995 Hunter and colleagues published articles detailing an ophthalmic virtual environment developed as part of a teleoperated microsurgical robot.[43,44] The virtual environment included anatomic, mechanical, and optical properties of the eye, which serves as an intermediary between the microsurgical master and slave and the active mannequin. The efforts of Hunter were quite advanced for their times, but further development is not documented in the literature.

Currently, the only ophthalmic virtual reality surgical training system on the market is EYESI produced by VRMagic (Fig. 7). EYESI was initially designed as a vitreoretinal surgery simulator with a mannequin head prop and vitrectomy and intraocular illumination probes,[46] but VRMagic wisely has adopted a modular approach in which a software application can be plugged into the system and allow for a breadth of ophthalmic surgical procedures. Efforts to expand EYESI have led to the addition of a capsulorhexis simulation that allows practice of the continuous curvilinear technique.[94,95] The vitreoretinal surgery simulator component was introduced in the 2003 American Academy of Ophthalmology Convention as a prototypal trainer. Currently, EYESI boasts vitreoretinal and anterior segment modules. The hardware

TABLE 1

Summary of Available Ophthalmic Virtual-Reality Surgery Simulators

System	Surgery	Visual	Haptics	Improvements	Trials
Rouland et al[74]	Retina laser photocoagulation	Monitor-based	No	None mentioned	Yes Peugent[68]
Sinclair et al[86]	Cataract extraction phacoemulsifier	Monitor-based	Yes	1. Refinement of the tactile feedback 2. Elimination of slight lag time between stylus movement and instrument movement in visual feedback system	No
Hikichi et al[39]	Vitreoretinal surgery	Monitor-based	Yes	1. Lowering cost - trying to replace high-speed graphics computer with standard pc 2. More simulated cases	No
Verma et al[92]	Vitreoretinal surgery	Monitor-based	No Lens touch depicted visually	Tactile feedback needed for system to be effective training tool - planning to use PHANTOM technology	No
EYESI VR Magic	Vitreoretinal surgery	Monitor-based	No Retina touch depicted visually	None mentioned	Yes Rossi[73] Jonas[46]
Laurell et al[50]	Cataract extraction phacoemulsifier	LCD display	Yes	None mentioned	No

interface with modules retails for approximately $80,000.

TRIALS

To our knowledge, only three published trials exist documenting the efficacy of virtual reality simulation in ophthalmology surgical training. As discussed previously, trials can be grouped from basic to complex into skill acquisition, differentiation, and VR to OR. Two of the documented trials to date have sought to establish face validity through skill acquisition testing,[46,68] and one has established discriminative validity.[73] To date practicality and transferability to the operating room have not been established through VR to OR studies.

Peugnet et al tested a retinal photocoagulation simulator by dividing 10 ophthalmology residents into two groups; the first received conventional training while the second group trained on the virtual-reality simulator. Results revealed that residents trained on the virtual-reality system required only 25.4 days of training compared with 42.25 days in the control group. All residents performed at a level compatible with patient safety and comfort. The authors of the trial conclude that their work is a "preliminary assessment and should be continued."[68]

VRMagic's EYESI vitreoretinal surgical simulator was studied in two different trials. Jonas et al randomized 14 ophthalmic residents and medical students into virtual reality trained and non-trained groups in a skill acquisition trial. The virtual reality trained group completed two training programs on the simulator. The first program consisted of navigating through the vitreous with the vitrectomy probe touching a series of red balls for 3 seconds each. The second program consisted of peeling an epimacular membrane from the retinal surface. The two groups then were evaluated in a wet-lab setting using pig eyes to perform vitrectomy. Parameters assessed were amount of vitreous removed, number of retinal lacerations, amount of retinal detachment, time to remove a foreign body, and a subjective score from an evaluator who was blinded to the group status. Unfortunately, none of the results were statistically significant but did show the virtual reality trained group to have a superior skill level in all aspects of the evaluation.[46]

Rossi and colleagues measured the simulator's ability to differentiate various levels of expertise in a navigation task, its learning curve, and the validity of its membrane-peeling scenario. Results showed a significant difference in completion time between students, residents, and experienced surgeons. The ability to learn the navigation task was demonstrated

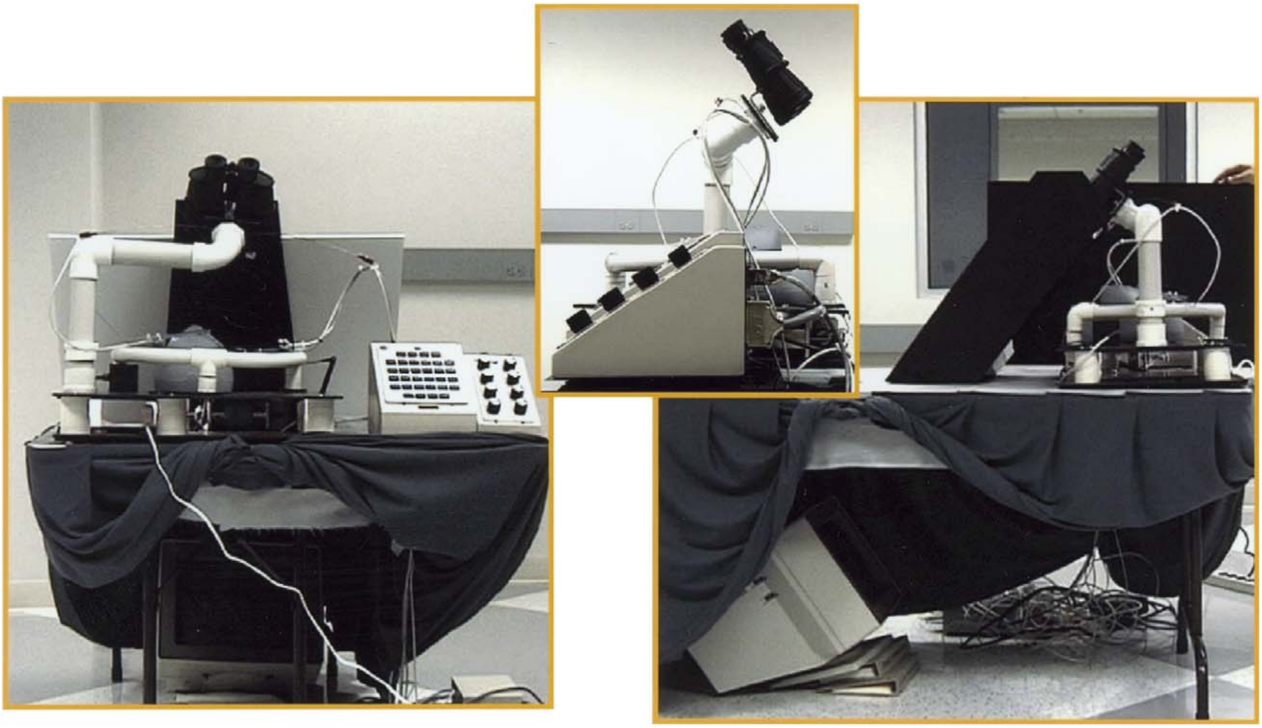

Fig. 3. Cataract surgery simulator developed in 1995 by a collaborative effort between the Georgia Institute of Technology and the Medical College of Georgia.

by a significant decrease in the completion time. The membrane-peeling task yielded a significant difference in average completion time and number of surgical mistakes.[73]

The promising trial results are an indication that virtual reality simulation might be the revolution our training programs are desperately in need of to cope with the ever-growing mass of surgical knowledge. Nonetheless, more trials on surgical simulators are required before a more definitive statement can be made. Future trials should assess the impact of virtual reality training on operating room performance.

ROLE OF VIRTUAL REALITY IN OPHTHALMOLOGY TRAINING

Traditionally, surgical residents develop their techniques and master the art of their practice in the surgical theater on live patients and under supervision, but pressure is mounting for a more formally structured, more financially manageable, and a more time efficient curriculum. It is our opinion that once VR to OR trials establish virtual reality simulation as an indispensable component of ophthalmology training, a public endorsement of virtual reality simulation by the American Academy of Ophthalmology, ABO, or residency commission may be imminent.

What role virtual reality will play in the evolution of our surgical curriculum is uncertain. The current apprentice system has served the art of surgery for over a hundred years, but the challenges we face with the exponential growth of surgical knowledge combined with time and financial stressors have led to a need for change. We foresee virtual reality working synergistically with our current curriculum modalities to streamline and enhance the resident's learning experience. Previous attempts in other surgical specialties to rely solely on virtual-reality training as a stand-alone teaching medium have been unsuccessful,[30] and we do not promote such a notion in ophthalmology training. Without doubt, virtual reality is more likely to be successful if it is systematically integrated into a carefully constructed education and training program that objectively evaluates technical skills proximate to the learning experience.[29]

One possible scenario is that the ophthalmologist-in-training is introduced to a given surgery as an assistant in the operating room followed by a wet-lab experience that is then reinforced by multiple hours on a virtual-reality simulator. The virtual-reality simulation would then be able to provide insight into the variations and nuances of the surgery with different clinical scenarios and complications. A similar approach was implemented in a general surgery training program using a GI endoscopy simulator with great success.[18] The ability to evaluate

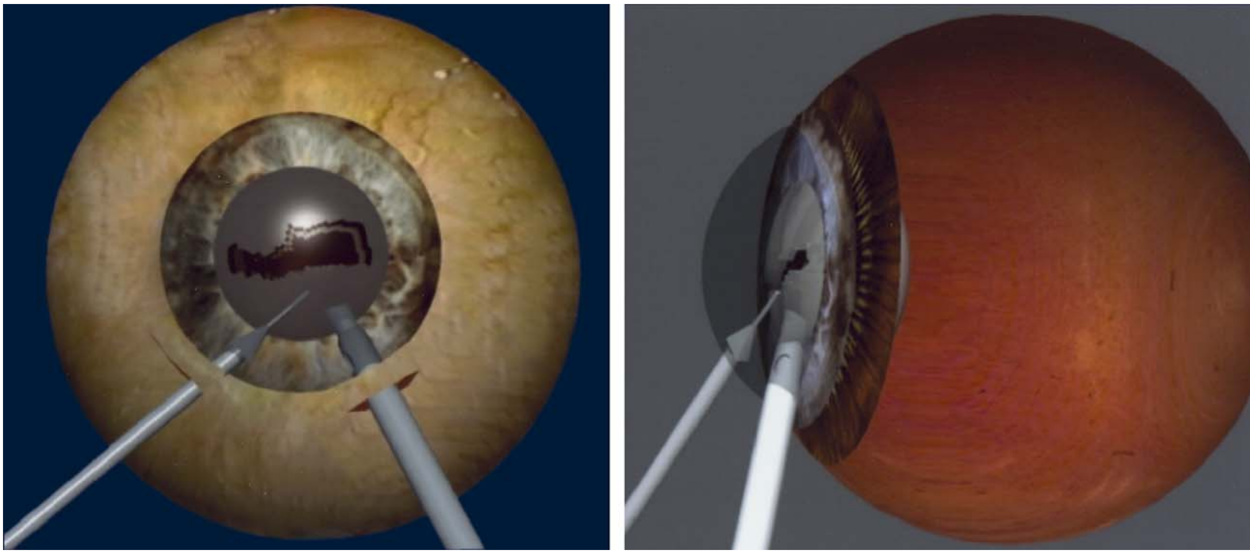

Fig. 4. GT/MCG eye surgery simulation models of the anatomy and surgical instruments.

residents in a fair, quantitative fashion with multiple assessments and minimal time commitment on the part of faculty will prove invaluable.

Many have argued that wet labs carry drawbacks that extend beyond financial burdens and extend to ethical issues relating to animal and cadaver tissue usage and the technical challenge of preparing a wet lab. Edema of the cornea[54] and inaccurate simulation of tissue consistency and anatomy[87] can make simulation difficult. If and when high-fidelity ophthalmology virtual-reality surgical simulators are developed, they will not carry the ethical obstacles inherent in the use of animal and human tissues in surgical simulation,[49] and they could be integrated with wet-lab experiences into a surgical training curriculum to minimize use of animal and cadaveric tissue. State-of-the-art, high-fidelity virtual reality might one day provide an experience that blurs the line between virtual and reality while negating the technical limitations of the wet lab. Virtual reality is, in essence, an extension of mannequins and wet labs, and is a natural evolution of training in our age of technology.

Technical Aspects

Advancements in computer platforms, imaging algorithms, tracking, and haptics are helping blur the line between virtual and reality in the field of surgical simulation. In order to create a realistic virtual environment, surgical simulations must accurately and efficiently model the surgeon's tools, the patient's anatomy, and the interaction between them in real time. A virtual-reality simulator involves the coordination of hardware, software, and human-computer interfaces (Fig. 8).

HARDWARE

With $30 billion in global sales in 2002 alone (Gaudiosi J: Games, Movies Tie the Knot. Wired News, 2003), the video game industry continues to propel development of desktop computer processing power. Current high-end desktop computers are able to run a real-time 3-D surgical simulation with haptic support. Datasets representing the virtual world can be maintained and manipulated without compromising high-resolution graphics. The new video cards available to the average consumer today

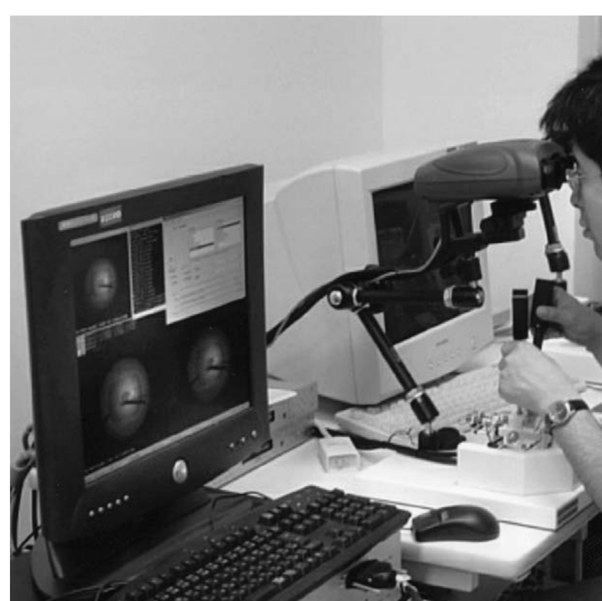

Fig. 5. Vitreous surgery simulator hardware setup developed in 2000 by the Department of Ophthalmology at Asahikawa Medical College, Japan. (Photo courtesy of Taiichi Hikichi, MD, Asahikawa Medical College, Japan.)

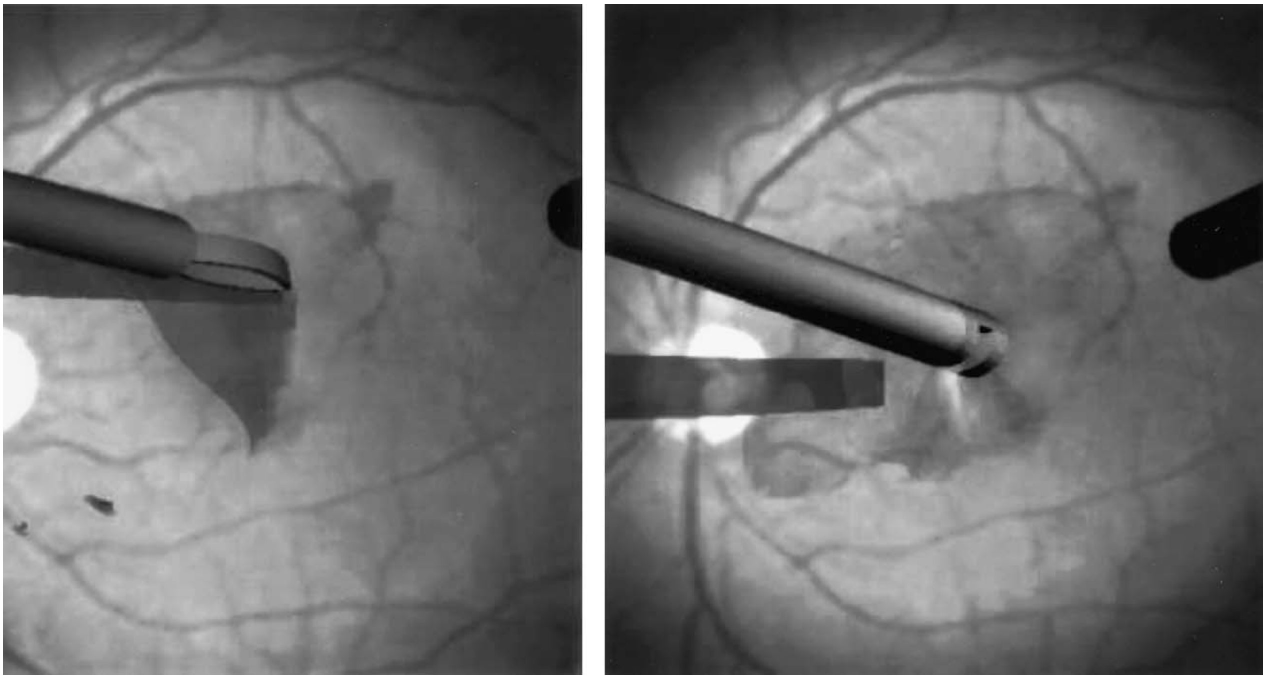

Fig. 6. Virtual world of a vitreoretinal surgery simulator developed by a Japanese group from Asahikawa Medical College. (Photo courtesy of Taiichi Hikichi, Asahikawa Medical College, Japan.)

have a graphical processing unit (GPU) similar to the central processing unit (CPU) of a computer.[5] The GPU handles most of the rendering responsibilities, freeing up the CPU for other tasks, such as collision detection, user interface, and controlling the haptic interface. The computational power available in today's high-end desktop allows users in a surgical simulation to interact with the environment via haptic devices in real-time.[72] The vitreoretinal simulator developed by Hikichi et al provides for real-time visual and haptic interaction through a personal computer platform,[39] thus demonstrating that ophthalmology surgery simulation can be delivered through a desktop computer (Fig. 5).

SOFTWARE

Surgical simulator software must model highly detailed parts of the anatomy, perform tool-to-anatomy collision detection and response, and provide the ability to prod, pull, or cut the virtual models (Fig. 9).[8]

ANATOMY

The models for the patient's anatomy can be created from 2-D images, such as the visible human project database. The use of patient-specific imaging data from MRI and CT requires the time-consuming task of segmentation. The development of a standardized method of segmentation has facilitated the transfer of data between imaging devices and graphics workstations more easily and accurately.[22,83] This might someday facilitate patient-specific simulation in which the surgeon can practice resecting an orbital tumor, for example, before even entering the operating theater.

PHOTOREALISM

The graphical models of the patient's anatomy are usually displayed as a mesh of polygons with a texture-mapped three dimension overlay. This technique of surface rendering gives images higher fidelity color and texture. The drawback to surface rendering is that the method does not maintain information about what lies below the surface; thus, the ability to surgically manipulate the object is lost. A more computationally expensive method is volume rendering the anatomy, which provides information about internal properties of the modeled structure.[38] In the creation of the ophthalmic surgery simulation virtual world, developers can utilize surface rendering for objects that will only be pulled and prodded while volume rendering can be utilized for objects that require cutting. For example, a simulation of vitreoretinal surgery would only require surface rendered eyelids, but a blepharoplasty simulator would require volume rendering of the eyelids.

BIOMECHANICAL MODELING

The literature abounds with mathematical descriptions of tissue biomechanical models.[9,16,24,60,70]

Fig. 7. EYESI® by VR Magic.

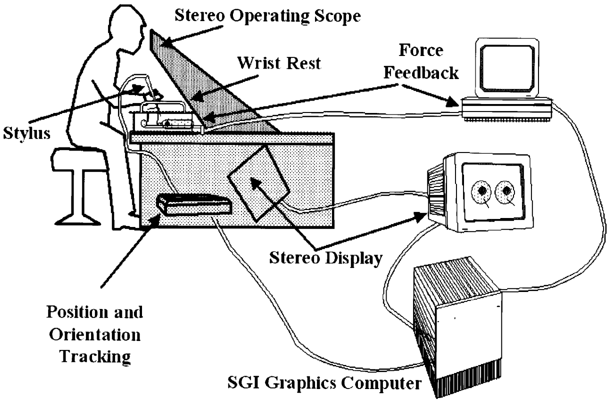

Fig. 8. Schematic of virtual reality simulator components and layout. The trainee sits at the controls looking through the stereo operating scope that peers down onto two separate images of the operating field. Each image is specific for the view from either eye, thus providing depth-perception. The SGI graphics computer is responsible for the visual rendering of the images displayed on the monitor. The surgeon interacts with a virtual eye using a virtual surgical instrument controlled by a handheld 3-D position-tracking stylus that continuously reports position and orientation to the computer. The tip of the stylus is connected to three motors that generate component force feedback in response to the tool-tissue interaction.

Each method has a tradeoff between computational expense and realism, and the exact balance between the two is an area of intense research.[13] The most demanding aspect of biomechanical modeling as far as computational power is concerned lies in the realm of collision detection.[42]

HUMAN–COMPUTER INTERACTION

The concept of human–computer interaction is essential to the immersive properties of any virtual environment. To provide a sense of verisimilitude depends on the interfaces presented to the user. If the user's senses find the virtual environment to follow the laws of physics that have been learned in the real world then the user will be thrown into a world of experience tailored to the goals at hand. The two most important components of the human experience for surgical simulation purposes are sight and touch, and they are the focus of this section.

VISUAL

The designer has several options when deciding on a visual display modality: monitor-based, projection-based, head-based,[36] and virtual retinal display.[93]

The monitor-based display utilizes a simple computer monitor to provide the visual output component, eliminating the need for expensive special equipment. Most of the developed ophthalmology simulators use monitor-based displays. Ophthalmic surgery simulation is simplified by the fact that the surgical microscope defines the field of vision and thus decreases the amount of graphical modeling required for surgical manipulation.[88] Simulation through the monitor-based display involves the production of two separate images reflecting the view from either eye on the surgical field. Each eye views the appropriate image exclusively; thus, the important visual queue of depth perception is provided.

HAPTICS

Simulation of touch carries tremendous importance in virtual reality surgical trainers despite the fact that sense of touch comprises approximately only 5% of sensory input.[17] The only developed ophthalmology trainers that utilize haptic feedback are the cataract surgery simulator[86] and the Japanese vitreoretinal surgery simulator.[39]

Surgical haptics are most commonly projected through a device mounted at the end of a robot arm. Grasped by the hand, the haptic device provides reciprocal resistance and force when manipulated. Most devices monitor where the hand is in space while providing appropriate resistance for the user's motion through the virtual world.[7] Many commercial haptic displays are available; one of the more popular ones is the PHANTOM[15] interface that affords force feedback in three directions with position sensing in six directions (Fig. 10). The PHANTOM has been used in many various simulators including surgical[71] and non-medical.

Conclusions

CURRENT CHALLENGES

Despite the tremendous progress made over the past 20 years in the field of surgical virtual-reality simulation, there remain challenges to be addressed.

INTERACTION WITH VIRTUAL WORLD

Many would argue that the current state of surgical simulation fails to replicate reality with adequate accuracy in visuals and haptics.[57,71,89] Efforts are being made to make high fidelity visual and haptic interaction available through high-end personal computers.[1] In the realm of surgical simulation, haptic interaction is essential, but the only commercially available simulator for ophthalmology training EYESI does not incorporate haptics to our knowledge.

LACK OF EVIDENCE

Whereas many published trials of virtual reality exist in the various surgical specialties, the literature is quite sparse when it comes to studies of ophthalmologic surgery simulators. The gold standard in trials is so-called "VR to OR" or virtual reality to operating room studies in which the impact of virtual reality training is measured in operating room performance. Currently, no study has been reported in the ophthalmology virtual reality literature that uses VR to OR. A dire need to establish the legitimacy of ophthalmologic surgery simulators through randomized, controlled VR to OR trials prevails. Just as the FDA, the Society for Cardiovascular Angiography and Interventions, the Society for Vascular Medicine and Biology, and the Society for Vascular Surgery all publicly endorsed the use of virtual reality simulation in carotid stent training once solid evidence was available, the ABO and AAO will embrace virtual reality simulation as an essential component in training and evaluating within the context of the surgical competency requirement once solid evidence exists.

LACK OF STANDARDS

The research community has not agreed upon a standard interface or software modality. The search for the most realistic, least computationally demanding, and most inexpensive method of virtual reality simulation has led to individual experimentation. Current trends appear to suggest that the level of innovation in virtual reality surgical training is reaching a plateau, but we are in need of standardized applications in the field of ophthalmology simulation.

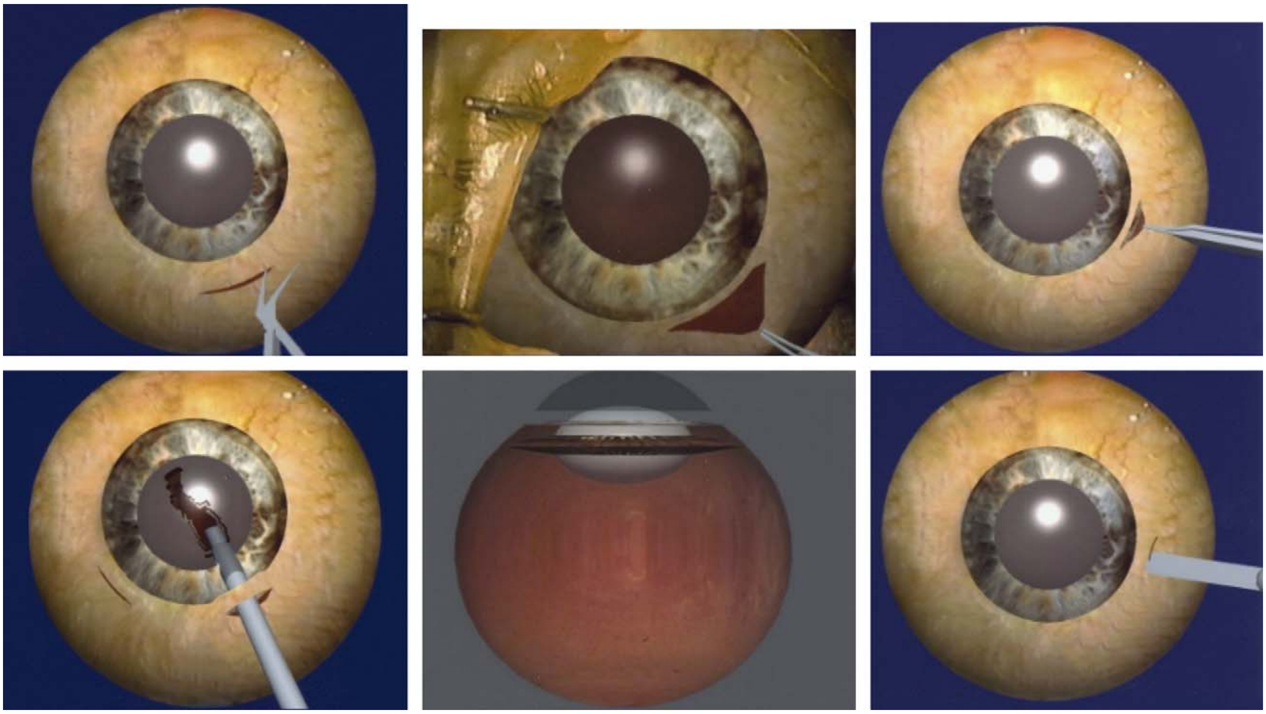

Fig. 9. Virtual environment visual display of eye anatomy and simulated surgical motions of cutting, pulling, and prodding in a cataract removal trainer.

Fig. 10. The PHANTOM haptic feedback device is an example of a haptic display device. (Photo courtesy of SensAble Technologies, Inc., Cambridge MA, USA. PHANTOM, PHANTOM Desktop, SensAble, and SensAble Technologies, Inc. are trademarks or registered trademarks of SensAble Technologies, Inc.)

AFFORDABILITY

Monetary obstacles stem from a lack of standards in the various virtual reality trainers reported in the literature. Once standards are established, the repurposing and sharing of system components and the resultant high return on investment will encourage training programs to institute virtual reality simulation in ophthalmology training curricula.[91]

FUTURE DIRECTIONS

Surgical Skills Training

In ophthalmology residency education, virtual reality could one day play an integral role in surgical skills training. It has the potential to provide a robust surgical training experience while cutting down operating room costs and minimizing the risks for patients. The ability to create models of a patient's anatomy gives potential of practicing patient-specific surgery prior to entering the operating room. In addition, the ability to recreate scenarios of surgical complications would be of utmost value, for the surgical resident does not always have the opportunity to attain proficiency in dealing with the mishaps that will inevitably occur at some point in any career.

Another point to be considered is when new procedures are introduced it takes time before attending physicians feel comfortable enough to teach those techniques to residents, which leads to a lag in transfer of knowledge. Provided that high fidelity virtual reality technology is developed quickly for new techniques, resident physicians and their mentors could practice cutting edge surgical methods earlier on and be more proficient in them before they enter the operating theater by practicing on a virtual reality simulator.

An additional intriguing facet is the possibility of grand rounds on the World Wide Web. One day it will be possible to transcend time and place and provide simulation of patient pathologies and surgical approaches. Imagine an online database of clinical cases accessible to simulation centers and sites that would provide an interactive electronic "grand rounds on the web."[41]

Surgical Skills Testing

Standardized surgical skill testing is of utmost value at the current time in which ophthalmology training is struggling to create quantitative measures of proficiency. It will likely find application in assessing medical students interested in becoming ophthalmologists and for re-licensing of the graduated ophthalmologist.

Medical students applying to ophthalmology residency might have to pass an assessment of surgical skill potential on a virtual-reality simulator as part of their application.

Ophthalmologists in training may be required to gain a certain proficiency on a simulator before being allowed to perform a live case. For licensure, they may have to pass a cataract extraction and intraocular lens implantation simulation as part of board certification. Didactic assessment of medical knowledge has been a standard component in our residency programs and beyond, but an objective assessment of surgical skills is lacking.

The average physician practices for approximately 30 years, and with today's exponential growth of information the half-life of medical and surgical knowledge is exceedingly short. To address this concern we have instituted continuing medical education (CME) requirements in all branches of medicine. Does not surgical education require such institutionalization with a continuing surgical education (CSE) requirement? The lack of means for objective evaluation has impeded such a requirement, but virtual reality may be the medium through which we can develop a continuing surgical education program. Graduated ophthalmologists may one day be required to pass a re-licensing assessment to assure adequate maintenance of surgical skills or to gain certification in a new technique.

Surgery Research

Virtual reality could be used as a controlled laboratory for testing new surgical techniques and refining the well established.

Strict adherence to the apprentice approach is no longer practical. Virtual reality may very well hold the solution for the mounting obstacles we face in developing a systematic and structured surgical curriculum. We must as a community of educators and learners embrace the technological advancements that will inevitably change the face of ophthalmology training forever.

Method of Literature Search

PubMed and OVID databases were searched from the years 1991 through 2005 with key words: *simulation, virtual reality, ophthalmology, surgery, and training* separately and in various combinations. Only peer-reviewed journal articles and book chapters were selected. Additional sources included articles cited in the reference lists of other articles. Foreign journal articles were included in our literature searches, but only English abstracts were used. No languages were excluded in our search of the literature.

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