JOURNAL OF ENDOUROLOGY
Volume 16, Number 3, April 2002
© Mary Ann Liebert, Inc.

Virtual Reality Surgical Simulation for Lower Urinary Tract Endoscopy and Procedures

MICHAEL J. MANYAK, M.D.,[1] KRISTIN SANTANGELO, M.D.,[1] JAMES HAHN, Ph.D.,[2]
ROGER KAUFMAN, Ph.D.,[2] THURSTON CARLETON,[2] XING CHENG HUA,[2]
and RAYMOND J. WALSH, Ph.D.[3]

ABSTRACT

***Background and Purpose*: To provide a realistic experience of lower urinary tract endoscopic procedures, we have developed and continue to expand a computer-based surgical simulator that incorporates a surgical tool interface with anatomic detail and haptic feedback.**

***Methods*: Surface-based geometric data for the lower urinary tract were generated from the National Library of Medicine Visible Human dataset. The three-dimensional texture map of the surface geometry was developed from recorded endoscopic video procedures. Geometry and associated texture maps were rendered in real time using the Silicon Graphics Extreme Impacts program. The surgical interface device incorporated all normal ranges of motion and resistance that occur within an actual operative environment. The hands-on endoscopic device attached to the interface device was provided by Circon-ACMI, Inc. Urologic residents evaluated the program for correlation with actual endoscopic procedures.**

***Results*: Texture-mapped digitized images provided a close anatomic similarity to actual videoendoscopic images. Virtual endoscopy of the lower urinary tract was reproducible and closely simulated actual visual and tactile endoscopic experience.**

***Conclusions*: Virtual reality surgical simulation is feasible for a variety of lower urinary tract procedures. This system coordinates visual perception with appropriate haptic feedback in both longitudinal and rotational axes. These types of procedures may be incorporated into future educational experiences for urologists to introduce new techniques and to provide documentation of surgical experience.**

INTRODUCTION

COMPUTER-BASED SIMULATIONS for clinical training have been utilized for medical education for more than 25 years with progression of technological advances from mainframe computers to the multimedia-based systems in current use.[1] Simulation becomes attractive whenever actual physical experience is associated with unacceptable risk or expense or the experience is not practical because of distance or temporal constraints. The classic example of the value of simulation in such circumstances is found in flight simulation for aviation training, first introduced during the Second World War to reduce the high casualty rate among the relatively inexperienced pilots recruited for aerial warfare. Although its development has occurred over 40 years, flight simulation in a virtual environment has only recently evolved sufficiently to be considered indispensible for training because of the savings and benefits in time, expense, equipment, and safety.

Surgical simulation is in its infancy, however, and remains relatively crude compared with the sophistication of the simulation experience for aviation. Despite comparison of surgical simulators with flight simulators, the technical aspects of accurate modeling of human anatomy and dynamic physiology to recreate the surgical experience present complex challenges separate from those of flight conditions. Another factor that has delayed rapid advances in the field of virtual reality (VR) surgical simulation is the cautious commitment of investment and resources by industry. The obvious marketing attraction pro-

---

[1]Department of Urology, The George Washington University Medical Center; [2]Institute for Computer Graphics, The George Washington University School of Engineering and Applied Science; and [3]Department of Anatomy, The George Washington University School of Medicine and Health Sciences, Washington, D.C.

vided by VR is tempered by the reality of measurable benefit to the surgeon. How does one measure objectively the incremental increase in technical skill that translates into a patient benefit? At what level is VR surgical simulation a cost-effective method of training?

Despite these limitations, the highly visual nature of the experience is an obvious attraction for use of a virtual environment (VE) to develop or evaluate surgical fine motor skills. The VR system is superior to most conventional interactive tools because it provides an added value with educational experiences that facilitate comprehension of complex spatial relationships of anatomic structures. Furthermore, the dynamic 3D manipulation of the VE can be customized for a particular patient by reconstruction of the exact individual anatomy from cross-sectional radiographic images. This exercise is not cost effective in most instances currently, but the expected advances in computing power and hardware make this goal attainable in the future. An additional advantage of the VR experience is the ability to practice repetitive maneuvers in a risk-free environment not provided in an actual surgical procedure, where the opportunity for repetition may not be appropriate or possible.

VIRTUAL REALITY SYSTEMS AS EDUCATIONAL TOOLS

Virtual reality-based programs cover a wide range of complexity, from immersive to non-immersive systems, depending on the hardware interface system employed.[2] Immersive systems utilize a stereoscopic visual display that changes in response to head and eye movements.[3] Typical components of immersive systems include a head-mounted display, instrumental "datagloves," position-tracking equipment, and haptic feedback.[4] Non-immersive VR systems, on the other hand, use a computer-based screen display that simulates looking into the virtual environment from an external vantage point. Interaction with a non-immersive system occurs in a limited fashion through a mouse or joystick, which may be used with a haptic device for tactile feedback. The goal of the educational program determines which system is more appropriate or realistic, and hybrid systems that employ elements of immersive and non-immersive systems generally have been more desirable to address medical educational problems.

Virtual reality technology has been viewed as an educational tool with tremendous potential in medicine because of the intuitive manner in which users can interact with virtual anatomic structures and control virtual physiologic events.[5–7] This more natural mode of interaction allows the user to concentrate completely on the environment and the problem posed of direct interaction rather than on the computer semantics.[8] It is also felt that VR may provide free-risk training experience simulated to reproduce the environment in which the particular skills will be applied. Virtual reality learning experiences, especially those with some component of immersion, appear to elicit perceptual and cognitive processes similar to those evoked through real-world experiences.[7–9] These characteristics make VR training very effective for visual–spatial tasks that relate the user motor actions directly to an effect in the simulated environment.

A key component of an authentic VR experience is the incorporation of haptic sensations that accompany every surgical procedure. This inclusion of haptic (tactile, proprioceptive, and force) sensation is one of the most challenging obstacles in VR development. Many methods of producing haptic sensation may be adequate in one aspect but fall short in others. For example, mechanisms that produce the sensation of pressure by inflation of tiny bubbles in a glove do not impart the sense of solidity of an object, because one can still project one's hand through the visual object without resistance. Endoscopic surgery appears to be a better target for VR development because the hardware interface is dependent on a focal point that acts as a fulcrum. Indeed, some of the earliest reports of surgical simulation with VR involved laparoscopic procedures.[10,11]

One can readily envision the application of VR technology to the discipline of urology, which is replete with endoscopic procedures that require finesse to achieve high-quality outcomes. It has been estimated that between 75% and 85% of urologic procedures have evolved or been supplanted within the last decade.[12] Rapid introduction of new techniques often places a burden on the urologist to adapt the technology or face economic competition. A single training exercise is often insufficient to gain significant experience for a more complex procedure, forcing the physician to complement learning either by advanced training or by trial and error. Compounding the problem is the dearth of useful training models in the absence of currently politically incorrect animals. These factors enhance the attraction for application of VR to surgical simulation.

Various reports have documented the interest in applying VR simulation in the urologic field ranging from anatomic reconstruction of the male pelvis to the development of a simulation of transurethral resection.[13–15] While these reports represent a spectrum of approaches to the development of a teaching tool, only one of these prototypes incorporates a haptic sensation component.[15]

Selection of lower urinary tract endoscopy for our simulation was based on the frequency of the procedure performed, the relatively more accessible anatomic data for the lower urinary tract, and the ability for objective assessment of performance.

DEVELOPMENT OF UROLOGIC VR SURGICAL SIMULATION

The training of urologic surgeons for lower urinary tract endoscopy occurs throughout the residency program with temporal improvement in technical skills required for graduation to the next level. While videoendoscopy has greatly facilitated teaching capabilities, there is no substitute for hands-on experience with the tactile sensations and subtleties of performing endoscopy. The value of the simulator lies in the ability to coordinate visual perception with appropriate haptic feedback in both longitudinal and rotational axes. Our technical objectives for urologic simulation of lower urinary tract procedures are categorized generally in three areas: construction of a software simulator, construction of the hardware interface device, and assessment of use in the training environment.

Software Simulator Construction

The four essential components of a VR surgical simulation are data generation, simulation of the physical interaction of instruments with tissue, visualization of the simulation, and user interaction with the simulator. The objective of data generation in this project was creation of the geometric anatomic structure of the lower urinary tract from radiographic data from an actual person. The dataset can be generated for any human being, but the Visible Human Project (VHP) from the National Library of Medicine, completed in 1993, was chosen because of its free access to an existing sizeable database. These VHP datasets are designed to serve as a common reference point for the study of human anatomy. The VHP use of 3D graphic capabilities allows sophisticated reconstruction and manipulation of complex images. Virtual colonoscopy and laparoscopy have already been demonstrated utilizing the datasets, and there are reports of reconstruction of the male pelvic anatomy from this database.[13]

The cadaveric subject of the male VHP was a 38-year-old man 71 inches in height and weighing 199 pounds with a surgical history of an appendectomy and left orchiectomy.[16] Magnetic resonance images (MRI) of the trunk and extremities were acquired in the coronal plane with a body coil, CT was used to obtain transverse images at 1-mm, 3-mm, and 5-mm intervals through the head and neck, thorax and pelvis, and lower extremities, respectively (Fig. 1). The male dataset is 15 gigabytes and contains 1871 digital axial anatomic images which also include multiple photographic images of carefully prepared cryosections of tissue in addition to the CT and MRI images.

The simulator system was developed on a Silicon Graphics Visual Workstation running Microsoft Windows NT. Because this is PC-based development, the resulting software will be available to a large audience. Another advantage to this system is that there are several interface cards commercially available for the hardware interface device. The surface-based geometric data for the lower urinary tract was constructed on a 3D mesh of nodes (Fig. 2). Each node defines its location relative to the position and rotational orientation of the endoscopic instrument. Three-dimensional texture maps of the surface geometry were developed from recorded endoscopic video procedures to provide the proper level of visual realism without sacrifice of real-time interaction. Geometry and associated texture maps were rendered in real time using the Silicon Graphics Extreme Impacts program. The simulation was designed to correlate haptic information with anatomic data and visual displays. Therefore, the operator would receive tactile, proprioceptive, and force feedback corresponding with the visual display.

Hardware Interface Device Construction

The surgical interface device incorporated all normal ranges of motion and resistance that occur within an actual operative

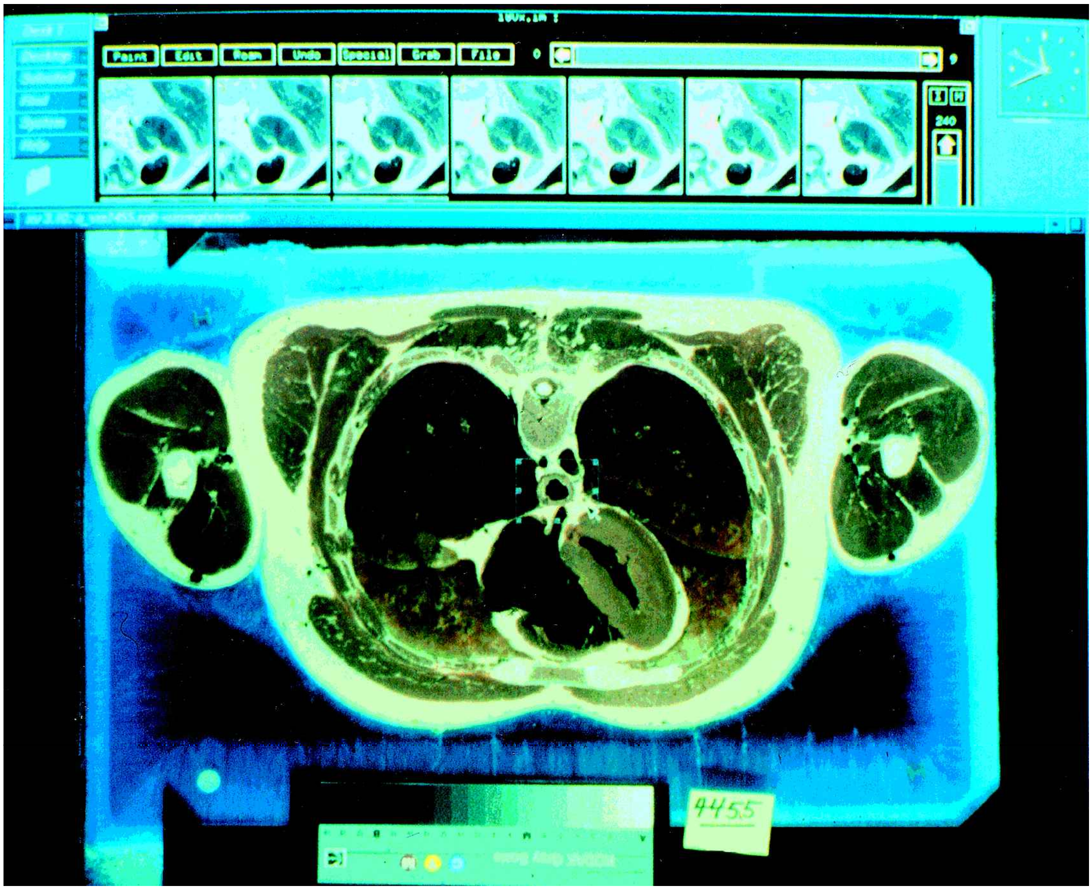

FIG. 1. Cross-sectional image of upper thorax in Visible Human Project from National Library of Medicine. Images were obtained at 3-mm intervals from thorax to pelvis.

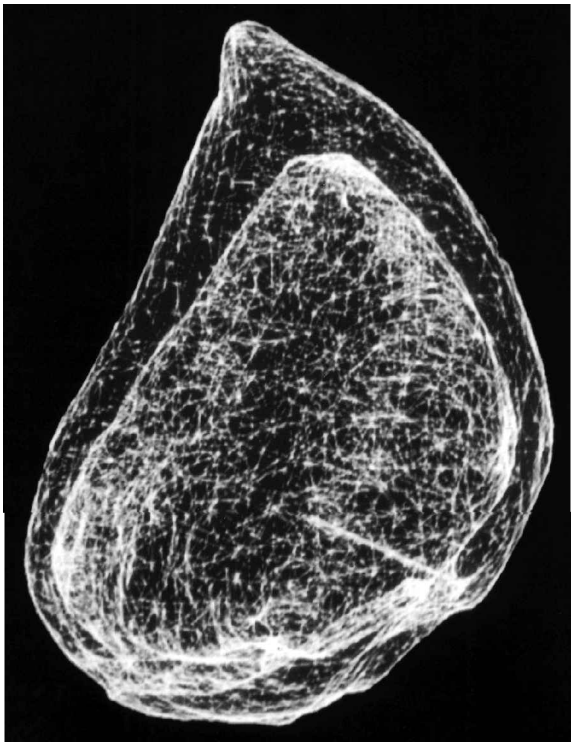

FIG. 2. Lateral view of 3D reconstruction of human bladder from Visible Human Project. Outer layer represents muscular layer of bladder. Note urethral opening at dependent portion at right side of bladder.

environment. The hands-on endoscopic device attached to the interface device was provided by Circon-ACMI, Inc. Users were able to vary the angle of the endoscope in the pitch and yaw directions and to advance or retract the instrument in a linear fashion, thereby providing four degrees-of-freedom simulation. Simulated tissue resistance to linear push on the endoscope was provided to the user by a computer-controlled linear braking device coupled to the simulation, which provided resistance directly proportional to the video image (i.e., tissue *v* lumen) and the spatial orientation of the endoscopic component. Therefore, the resistance varied with the tissue viewed on the video display to simulate the tissue resistance encountered during an actual endoscopic procedure. For example, there was significant resistance to advancement of the endoscope when the image showed that the endoscope was directed at prostatic tissue. However, if the image projected the urethral lumen, much less resistance was encountered. There was always some resistance encountered once the endoscopic device was placed in the interface device, much as one would experience when an endoscope is in place within a body cavity and held in place passively by contact with tissues when not in use.

Evaluation of the Training System

Assessment of the simulator in the pilot stage was accomplished through exercises using eight urology residents in various stages of their training. There were two residents in each year of a four-year urology residency program who participated in the exercise, thereby providing responses from both relative newcomers to endoscopy as well as seasoned endoscopists. Each resident was asked to independently perform endoscopy of the lower urinary tract traversing the male urethra across the prostate and into the urinary bladder. The participants performed the exercise at least three times each before assessment. This was followed by a 17-question written evaluation that assessed the hardware interface device and video components for characteristics relating to similarity of design to existing endoscopic instruments, each of use, visual orientation, reality of tissue resistance during advancement, and resemblance to anatomic structures. A final question related to an overall comparison of the simulation with an actual endoscopic procedure.

RESULTS OF EVALUATION

The results of the evaluation of the prototype for urologic endoscopy revealed that VR surgical simulation is feasible for a variety of lower urinary tract procedures. There was a very rapid learning curve for use of the simulator, which suggested the device and video component closely resembled equipment familiar to the participant. This was reflected in the evaluation, where the system was judged to be very similar in appearance to existing cystoscopes and to have rotational movement that simulated that experienced in cystoscopy. Resistance appeared to be moderately similar to the real-time experience, and the system was deemed easy to use. Ease of use and similarity to an endoscopic procedure correlated with resident level of experience, with the senior residents rating the haptic component more realistic.

The video components were familiar to the evaluators and provided relatively good clarity of image, while satisfaction with anatomic structures varied. For instance, the initial texture-mapped bladder mucosal images were felt to be significantly improved in authenticity in later renditions when the outlines of the rather prominent mucosal blood vessels were softened. There was no difference across resident level of experience with evaluation of video components, which were mixed. The overall conclusion was that, despite an imperfect initial visual presentation, the simulation did generally duplicate the experience of urologic endoscopy. The consensus was that further refinements would allow this simulation program to approximate those procedures very closely. Because simulation is not designed to be an exact replica but rather to impart the experience one receives during performance of a task, this simulation was deemed to have accomplished that goal.

THE FUTURE OF VR SURGICAL SIMULATION

The recent prediction of widespread use of VR-based applications for surgical simulation by the new millennium has fallen a little short of expectations, but the potential for this technology as a surgical educational tool remains intriguing, especially for image-guided procedures such as endoscopy, laparoscopy, and interventional radiology.[3] Although simulation for open surgical procedures currently lags behind image-guided applications because of the even greater demand placed on high-fi-

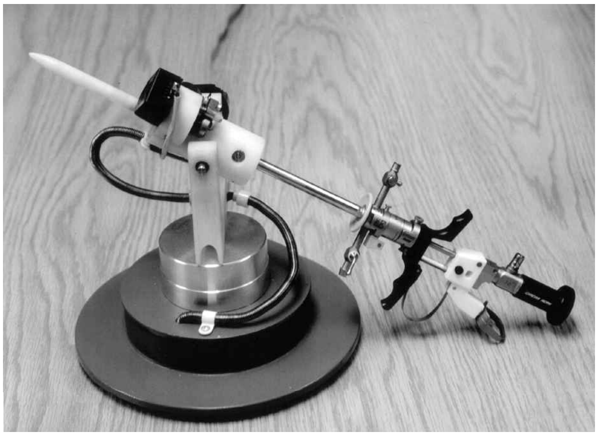

FIG. 3. Hardware interface device for lower urinary tract endoscopy simulation, which allows four degrees of freedom and provides haptic experience to simulate tissue resistance.

delity resolution, it is not unreasonable to assume that these types of simulations will be of sufficient quality for practical use in the relatively near future as the predicted quantum leaps in computer technology are introduced.

One obstacle to the development of VR surgical simulation for open procedures is the incorporation of the haptic component because of the variability of range of motion possible in an open procedure. Solving this problem will be a key issue for open surgical procedures, and endoscopic surgery appears to be the most logical target pending advances in VR haptic technology. The simulation of endoscopic resection and other surgical tasks is much more feasible with a fulcrum as the entry port for instruments such as is experienced during endoscopic procedures. Our braking device supplies the appropriate haptic sensation to recreate the tissue resistance experienced during resection and insertion of instruments (Fig. 3).

The use of VR-based medical educational tools has been projected to be applicable to a variety of situations. The obvious use for resident education is attractive in light of the documented decreased performance of certain core procedures at the end of residency that require significant repetition, such as transurethral resection. However, this extension of computer-based learning can be used for assessment of the user's technical and decision-making skills only if appropriate performance standards for psychomotor skills and behavior are developed and codified.[17] Similar but equally challenging requirements must be met before this type of computer-based training will be acceptable for physician certification for hospital privileges, board certification, and introduction of new techniques. Again, measurable benefit will be a key issue in the assimilation of VR-based simulation.

It is clear that this technology can be adapted for a wide range of urologic procedures that require endoscopy. The modular design of both the software and the hardware interface device will allow significant transfer of data for application to other endoscopy-based procedures such as ureteroscopy, transurethral resection of both bladder lesions and the prostate (Fig. 4), thermal ablative procedures, and placement and removal of internal devices. Caution must be exercised, however, about extrapolation from the development or applicability of one simulator transfers to another task, as each one of the aforementioned procedures requires a different set of psychomotor skills with a different objective. While one can be optimistic about the feasi-

FIG. 4. Simulation of electrocautery loop at virtual bladder neck.

bility of such transfer, the development of each individual program will require significant effort, resources, and financial support. To make these procedures more than a carnival sideshow at a medical convention requires commitment from industry and dedication from academia. The impetus for adoption of VR-based technologies will most likely come after demonstration of measurable benefit for the practitioner or patient.

ACKNOWLEDGMENT

This work is supported by a Research Enhancement Award from The George Washington University.

REFERENCES

1. Friedman CP. Anatomy of the clinical simulation. Acad Med 1995;70:205–209.
2. Bricken M. Virtual reality learning environments: Potential and challenges. Comput Graphics 1991;25:178–184.
3. Hoffman H, Vu D. Virtual reality: Teaching tool of the Twenty-First Century? Acad Med 1997;72:1076–1081.
4. Burdea G. Force and Touch Feedback for Virtual Reality. New York: John Wiley & Sons, 1996.
5. Durlach NI (ed). Virtual Reality: Scientific and Technological Challenges. Washington, DC: National Academy Press, 1995.
6. Middleton T. Applications virtual reality to learning. Interact Learn Int 1992;8:253–257.
7. Winn W. Designing and using virtual environments: The advantage of immersion. In: Proceedings of the Association for the Advancement of Computing in Education. Charlottesville, VA, 1994, pp 695–699.
8. Psotka J. Immersive tutoring systems: Virtual reality and education and training. Instruct Sci 1995;23:405–431.
9. Dede C. The evolution of constructivist learning environments: Immersion in distributed, virtual worlds. Educ Technol 1995;35:46–52.
10. Satava RM. Virtual reality surgical simulator. Surg Endosc 1993;7:203–205.
11. Coleman J, Nduka CC, Darzi A. Virtual reality and laparoscopic surgery. Br J Surg 1994;81:1709–1711.
12. Manyak MJ. Endoscopic future perspectives: Light as a diagnostic tool. In: Sosa RE (ed): Textbook of Endourology. Philadelphia: WB Saunders, 1996, pp 206–214.
13. Brooks JD, Chao W-M, Kerr J. Male pelvic anatomy reconstructed from the Visible Human data set. J Urol 1998;159:868–872.
14. Ballaro A, Briggs T, Garcia-Montes A, MacDonald D, Emberton M, Mundy AR. A computer generated interactive transurethral prostatic resection simulator. J Urol 1999;162:1633–1635.
15. Hahn J, Kaufman R, Carleton T, Hua XC, Manyak MJ, Walsh RJ. Virtual reality surgical simulation for lower tract endourologic surgery (abstract). J Urol 1999;161:303.
16. Spitzer V, Ackerman MJ, Scherzinger AL, Whitlock D. The visible human male: A technical report. J Am Med Informat Assoc 1996;3:118–130.
17. Higgins GA, Merrill GL, Hettinger IJ, Kaufman CR, Champion HR, Satava RM. New simulation technologies for surgical training and certification: Current status and future projections. Presence 1997;6:160–172.

Address reprint requests to:
Michael J. Manyak, M.D.
Dept. of Urology
The George Washington University Medical Center
2150 Pennsylvania Ave. NW
Washington, D.C. 20037