Telesurgery, Virtual Reality and the New World Order of Medicine
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Medical applications for the 21st century based upon the information infrastructure are just beginning to emerge. These include telepresence surgery, virtual reality (VR) surgical simulators, medical informatics, and rehabilitation. These applications are mediated through the computer interface and as such are the embodiment of the paradigm shift in the field of medicine.

The Green Telepresence Surgery System consists of two components, the surgical workstation and remote worksite. At the remote site there is a 3-D camera system and responsive manipulators with sensory input. At the workstation there is a 3-D monitor and dexterous handles with force feedback. The VR surgical simulator is a stylized recreation of the human abdomen with several essential organs. Using a helmet mounted display and DataGlove TM, a person can learn anatomy from a new perspective by 'flying' inside and around the organs, or can practice surgical procedures with a scalpel and clamps. The power of medical informatics is most mature in 3 areas: 1. Decision support (clinical associate systems) through artificial intelligence, 2. Distributive, collaborative, interactive networking, and 3. Compatibility of massive heterogenous databases. Rehabilitation medicine is using VR to permit impaired individuals to explore worlds otherwise not available to them, allows accurate assessment and therapy for their disabilities, and helps architects understand their critical needs in public or personal space. And to support these advanced technologies, the operating room and hospital of the future will be first designed and tested in virtual reality, bringing together the full power of the digital physician.

INTRODUCTION

The King is dead; long live the king. Medicine is dead; long live medicine. Whenever a dramatic change occurrs, there is the perception that the old is cast aside to be replaced entirely by the new. In a technologic sense, this is occurring today in medicine. From one perspective, it could be said that there is no medicine, but rather information infrastructure with a medical flavor. And, of the many disciplines arising from this new information era, virtual reality (VR) holds the greatest promise.

We are in the midst of a fundamental change in the field of medicine, which is enabled by the information revolution. Although the information age has been with us for decades, it took a major clinical event to propel medicine into this revolution. That major pivotal point was in 1989 when the first laparoscopic gallbladder operation was performed. The acceptance of this procedure was given by the patient, who benefited from having an operation to remove internal organs that resulted in no scars, essentially no pain, immediate return home (many of these operations are done as outpatient surgery) and return to work in a week or less (instead of 6 weeks). In order to perform the surgery, a miniature camera on a tiny "scope" is inserted through the umbilicus into the abdomen; this requires the surgeon to look at a video monitor (rather than the actual organs), where the images of the internal organs are displayed, and manipulate long instruments through tiny holes in the abdominal wall. The surgeon is actually removing internal organs without ever seeing or touching them. What makes this possible is the electronic, video image of the internal organs, and it is this digital image which represents the fundamental change in medicine. And while the use of imaging technology is new to the surgeons, it has long been available to other physicians. Radiologists have been viewing digital images for years, but the CT and MRI scans were viewed as an end in themselves, not simply a portion of a much larger patient care. Likewise, hospitals have been computerizing their entire administrative and record keeping tasks: however this "medical informatics" was yet one other isolated area of information management. Although networking has been available for decades, it has been limited to sending text and, on occasion, images.

THE PARADIGM SHIFT

Now is the time that all of these separate elements (laparoscopic surgery, digital imaging, electronic databases, and networking) are coming together, and the common focal point is the video monitor at a physicians workstation.[1] The video monitor is the portal into the entire world of information; this "electronic interface" will bestow power beyond imagination. The following is a scenario of the enormous implication of the medical revolution, which is beginning to rise now on the backbone of the enabling technologies of massively complex information database engines (the National Information Infrastructure), the power of supercomputers (High Performance Computing and Communication), and the pervasive, distributed, gigabyte telecommunication network or "information highway" (the Global Grid).

Although the current portal into this information rich arena is the video monitor, in the future, other display technologies such as head mounted displays (HMD), video-glasses, holograms, palmtop computers, etc. may be the interface. This interface is also the point of intellectual enhancement for it is here that all the information can coalesce and be presented to the individual as knowledge, not data. This interface can not only bring in information but can also send out information or commands for action in the real world (teleoperation or remote manipulation enables a person to work at a distance). As an example, a surgeon could be at the monitor during a real operation, doing a surgical procedure in the next city, and collaborating with another surgeon on the same patient. It would be possible to operate at a place which is too distant or dangerous, such as the space station or third world country. In taking this approach, we are able to "dissolve time and space", the physician can "be" at a distant place at the same time as another person without needing to travel there. But of utmost importance is the fact that the physician can simultaneously bring in many different digital images, such as the patient's CT or MRI scan, and fuse them with real time video images, giving the surgeon "Xray vision". Before doing a surgical procedure the surgeon could sit at the workstation and practice on a virtual patient (see below) to simulate the operation, then flip the switch and begin operating on the real patient with precisely the same workstation — this is the power of the electronic interface and the core technology for the medical revolution.

Virtual reality is the manifestation of this technologic paradigm shift. By working through the interface the physician is entering into a virtual environment, a cyberspace, While not comprehensive, the following represents the current status of many of the applications of VR in medicine.

SURGICAL APPLICATIONS

In the area of remote surgery, Dr. Philip Green [2,3] of SRI, International, has invented the Green Telepresence Surgery System. This consists of a remote operative site and a surgical workstation. There is 3-D vision, dexterous precision surgical instrument manipulation, and input of force feedback sensory information. Although this is actually telepresence rather than

VR, the surgeon is operating on a virtual image in front of him/her. In this manner the surgeon's abilities are enhanced and surgery can be performed with greater skill and precision. The current generation system is a one handed 5-DOF system with paired CCD cameras for stereovision; the next generation will have two 6-DOF surgical hands and a stereoscopic laparoscope to replace the fixed cameras.

Before performing a procedure, a surgeon can preplan an operation or a radiologist can precisely locate a radiotherapy beam. For the former, Dr. Joseph Rosen [4] ,of Dartmouth University Medical Center, has a VR model of a face with deformable skin which allows the practicing of a plastic surgical procedure and demonstration of the final outcome before making the incision on a patient, and Dr. Scott Oelph [5] has a virtual model of a lower leg upon which he can practice a tendon transplant operation and then "walk" the leg to predict the short and long term consequences of the surgery. Likewise, Dr. Antobelli[6] ,of Brigham Women's Hospital has developed a system that creates 3-D images from the CT scan of a child with bony deformities of the face (cranio-facial dysostosis); using this 3-D model, the bones can be correctly rearranged to symmetrically match the normal side of the face, permitting repeated practice of this extremely difficult procedure. In neurosurgical applications, Dr. Ferenz Jolenz [7] of Brigham Women's Hospital has provided the capability for 3-D MRI scan of an individual patient's brain tumor. At the time of brain surgery, the MRI scan is fused with the video image of the patient's actual brain, thus giving "X-Ray vision" of the tumor which is not otherwise visible where it is deeply embedded in the brain tissue. For the radiotherapist, Dr. Henry Fuchs [8] of the University of North Carolina has created a VR model which allows the physician to visualize the tumor (from reconstructed 3-D CT scans) inside the individual patient and plan various radiation trajectories to allow lethal doses of radiation to the tumor while avoiding damage to normal organs. These examples are but the first of many potential applications of VR for medical and surgical therapy.

It is the area of medical education and training where VR may reap the greatest benefits. There are two areas from which VR originated, flight simulation and information visualization (or the need to understand massive volumes of information and databases). Both of these components contribute to medical education. The latter will be to help medical students understand, through 3-D visualization, important physiologic principles or basic anatomy and the former can provide training in medical and surgical procedures. In addition, VR can be both a didactic and experiential educational tool. A demonstration mode could give a "tour" of the intended subject and then an exploration mode would allow the student to actually experience the environment. This latter method allows not only the reinforcement of information, but promotes initiative in learning through the thrill of discovery: the power of this approach has been proven repeatedly through experiments such as the Exploratorium of San Francisco. By "seeing" a visual representation of shock or navigating through the arterial tree the student could get a perspective of medicine well beyond anything that could be read from a book or even from dissecting a cadaver. There are currently efforts by Dr. Helene Hoffman [9] of University of California, San Diego, to create a 4-dimensional educational tool, the three dimensions of a virtual world (3-D space) and the fourth dimension of time (archived information in multimedia format) — in essence, multimedia virtual reality (MMVR). For example, in an MMVR simulator of the gastrointestinal tract, a student could "fly" down into the stomach, see an ulcer and "grab" it as if for a biopsy. This would bring up the histologic micrograph of an ulcer, or play a video tape of a Billroth 2 operation for ulcer disease, or perhaps demonstrate (predict) the healing in response to medication. In this fashion the multiple layers of understanding could be drafted into one, and the change of the processes over time can be graphically represented and personally experienced. Virtual environments can satisfy the need for training in medical and especially surgical procedures.

For decades, pilots have been training on flight simulators which have become so sophisticated and realistic that hundreds and thousands of "perfect" take-off and landings can be safety performed before their first real flight. So, too, will the surgeon of the future be able to perfect surgical skills before operating on the first patient. There are a few VR surgical simulators now appearing. In response to the need to train surgeons in laparoscopic surgery, Woods [10] and Hon [11] have developed virtual reality laparoscopic surgery simulators. These consist of a simple plastic torso into which the handles of laparoscopic instruments are mounted (to provide force feedback): the virtual abdomen (liver and gall bladder) is graphically demonstrated on the video monitor, and the apprentice surgeon can practice the specific laparoscopic surgery procedure. A different approach has been taken by Satava [12]: a virtual abdomen has been created for the immersive, traditional helmet mounted display (HMD) and DataGlove TM. Using virtual scalpel and clamps, the abdominal organs can be operated upon. This same abdomen can be "explored" by a student in the manner described above. The realism of the graphics of all simulators are cartoon level: but then flight simulators took 40 years to go from the carnival ride model of Edwin Link to the ultra realistic 747 simulators of today. Hopefully the surgical simulators will progress faster as computing power increases.


The remote worksite with a surgical nurse assisting the telepresence robotic instruments.
The remote worksite with a surgical nurse assisting the telepresence robotic instruments.


The surgeon at the surgical console, manipulating the master handles.
The surgeon at the surgical console, manipulating the master handles.

The second generation simulators now have organs with physical properties, such as visco-elastic deformation, collision detection, and higher fidelity of visual realism using texture mapping. The third generation simulators, which are to bring physiologic properties such as bleeding or leaking of various fluids, are on the drawing boards. Perhaps the following generations will bring (Generation 4) microscopic anatomy such as micro-glandular or neurovascular structures and (Generation 5) biochemical system modeling such as immunologic, endocrine or pathologic states of shock (Table 1).

There are 5 areas that contribute to the realism of a virtual world (Table 2): 1. Fidelity (high resolution of the graphics). 2. Organ properties (deformation from morphing or kinematics of joints) 3. Organ reaction (such as bleeding from an artery or bile from the gall bladder) 4. Interactivity (between objects such as surgical instruments and organs) 5. Sensory feedback (tactile and force feedback). Today the simulations must trade off (eg, less realism for more realtime interactivity) because of limited computing power, but the future holds promise of a virtual cadaver almost indistinguishable from a real person.

The third application for VR is in visualization of massive medical databases. Henderson [13] has created a cyberspace representation of the war injuries from the Viet Nam Database. Using a 3-D cube to plot 3 axes of information, complex combinations of war wounds, organ systems injured, mortality, etc. can be visualized as clusters of data points. These clusters can illustrate and reveal important relationships which otherwise cannot be discovered. Navigating in three dimensions allows different perspectives of the data, permitting different interpretations. This application for visualization has not been exploited sufficiently and holds promise for the field of medical informatics.

The use of VR for rehabilitation in medicine has grown dramatically, resulting in an annual conference for VR and rehabilitation. Greenleaf [14] has created virtual environments for exploration in a wheelchair. Warner [15,16] has utilized an eyetracker device from BioControl. Inc. in a quadriplegic child in an effort to provide her with the opportunity to develop interactions with the outside world before her disability causes her to become too introverted to communicate. In these circumstances, VR is being used to empower those individuals with disabilities.

There is an interesting area being developed using VR that is building an important foundation for the medical infrastructure. Dr. Kenneth Kaplan of the Harvard Graduate School of Design is beginning to apply VR to architectural design in a project for the operating room (OR) of the future. The great change in medicine and surgery alluded to above requires an OR and hospital that is not only worthy of this advanced technology, but capable of supporting it. An entirely new environment must be created based upon radically different concepts and the implementation of surgical and minimally invasive (or even non-invasive) therapies. Entirely new space configurations, the use of smart materials and intelligent equipment and the integration of information infrastructure, knowledge based decision support, imaging systems and advanced therapeutic modalities will be required to support the new generation of interventional therapists. In order to afford the widest possible opportunities to assess the impact of current and future technologies, the OR will be entirely planned using VR, giving architects, hospital administrators, surgeons, anesthiologists, operating room personnel and other key individuals the opportunity to "test" the OR before building it. Not only will the focus be designing an entirely new environment, but it will be patient based, insuring that the OR will be integrated into the whole of hospital care and be focused upon human scale and sensitivity.

Advanced technology is improving many aspects of medicine, and the ultimate direction and outcome will not be determined by the state of the technology but the intangibilities of personal, social and political will. In this atmosphere, the challenge is to ensure that the beneficiary of these remarkable technologies is the patient not the system or bureaucracy.

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