Chapter 55.
MEDICAL APPLICATIONS
of
VIRTUAL REALITY

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The benefits of virtual reality (VR) to healthcare can be summarized in a single word: revolutionary. The Information Age has yet to arrive for Medicine, and the infrastructure put in place by other disciplines and industries can be used to leapfrog into the next generation of healthcare. The most pervasive aspect of VR will be the core technology of interactive 3-D visualization. Those aspects of VR which are relative technologies, such as whether the experience is immersive, augmented (see through) or, whether the display is an head mounted display (HMD), 3-D video monitor, or room-sized Cave Artificial Virtual Environment (CAVE) or whether the experience is on a local computer or distributed over the Internet, are analogous to peripherals that can be used to customize the VR application to best suit the healthcare provider or patient. While there are many different ways to classify the medical applications, one that incorporates the essentials for the practice of medicine provides an excellent framework. The key components are diagnosis, therapy, education and training and the medical record. However, it is essential that the implementation of these applications is totally integrated and that the full spectrum of healthcare is incorporated. One method to accomplish these two goals is through the 3-D representation of the patient as a virtual person or “medical avatar”[1]. The greater the amount of data used to recreate the “information equivalent” of the person, the higher the fidelity of the representation and the more accurate and useful for patient care.

The origin of digitally representing a person derives from two sources: Nicholas Negroponte’s concept of “bits instead of atoms”[2], whereby an object in the real world (atoms) can be represented in the information world by a computer image (bits), and Dr. Michael Ackerman’s program from the National Library of Medicine of The Visible Human [3], which is an actual person who was scanned in three modalities (computed tomography, magnetic resonance imaging, and phototomography) to provide a full 3-D information equivalent computer image[4]. As more and more of the medical technologies become information based, it will possible to represent a patient with higher fidelity to a point that the image may become a surrogate for the patient – the medical avatar. The practice of medicine can take advantage of the power of the science of modeling and simulation and optimize the patient care by first performing upon the surrogate until the best solution is achieved, then providing personalized quality care. The initial accomplishments will be at the macro level for the whole body, organ and tissue systems;

then further levels of glandular structure, molecular, biochemical and genetic information can be added. With each increase in information, the validity of the model will improve and hence the quality of the patient care and the value of the model. In order to illustrate the power of this approach, the following scenario is offered as a reference framework of how the total spectrum of care can be completely integrated. For the purpose of identification, this framework is called the Doorway to the Future, and may require 20, 50 or even 100 years to achieve[5]. It is not possible to ever complete such a project, since modeling the human organism can always have more information derived for greater fidelity.

As a patient visits a physician, they will pass through a doorway in which numerous sensors and imagers are embedded, such as CT or MRI scan, ultrasound etc. Until this is accomplished, pre-visit scans will be accumulated. When the person sits at the desk, non-invasive vital signs and biochemical data will be acquired, just as we use pulse oximetery today to acquire heart rate, oxygen saturation and other values. All the information and images will be collected in a database, and then between the physician and the patient a holographic image of the person will be displayed, just as Dimensional Media Associates suspended holographic image[6] (Figure 1). This will be the medical record, a visual database with all of the information contained within the image. It is simultaneously the interface – an intuitive method of query. After the patient provides the history of illness and physical exam, the physician can interact with the image (similar to visual databases today) to obtain information. If the person complains of right upper quadrant pain, the image can be made transparent and the liver directly queried for relevant laboratory data such as liver enzymes, alkaline phospatase or bilirubin, as demonstrated by Engineering Animation, Inc[7]. If there are any abnormalities noted, the physician can use the image for diagnosis by performing a virtual endoscopic procedure to look for abnormalities. There are numerous physicians performing the clinical comparison of conventional video endoscopy to virtual endoscopy (see below, virtual endoscopy). If an abnormality is found, the physician can use the image for patient education to show and explain the patient’s problem – the image is now a patient education tool. If the abnormality will require a complicated operative procedure, the image can be used for pre-operative planning as is done by Taylor et al[8], or imported into a surgical simulator like Levy, et al[9] and used to optimize the surgical procedure for that specific patient. At the time of surgery, the image can be imported into the procedure using data fusion with a video image of real-time surgery, providing assistance with intraoperative stereotactic navigation as is performed at the Brigham Women's Hospital by Jolesz, et al.[10]. Finally, when the patient returns for follow up weeks after the procedure, a complete scan is once again performed, the database will perform data fusion and digital subtraction like Grimson, et al[11], with the difference being automatic outcomes analysis. The power of this scenario is that it provides a framework for the technologies that encompasses the full spectrum of healthcare, and integrates the information equivalent of the patient into a single record continuous across time. It can be updated as needed, and made available to the patient on a personal credit card sized record, like the military's Personal Information Card (PIC), or perhaps contained on a secure webserver on the Internet and available for global consultation through telemedicine.

The virtual environment technologies and applications that support this framework can be discussed within the context of the provision of medical care, mainly for diagnosis, therapy and education and training. However, there is overlap in many of these areas, for education and training is increasingly being embedded into the actual devices which are being used for diagnosis and therapy. An example is ultrasound (Figure 2), where the real-time image from a procedure is replaced by an archived image of an actual patient, and the student scans a mannequin as an ultrasound simulator with the same equipment and in precisely the same manner as an actual patient[12]. It is imperative to understand that the utilization of virtual environments is in the infancy, and the following applications are just the beginning of the new direction. Many are in the laboratory investigation, beta prototype or clinical investigation stage; few have been inserted into routine clinical practice. The furthest developed of the applications are undergoing rigorous and stringent testing and evaluation for technical and clinical efficacy, for Food and Drug Administration (FDA) approval and for cost effectiveness. It is unclear which will succeed in this arduous process for full time clinical practice.

Diagnosis using virtual endoscopy is one of the areas which will achieve clinical efficacy in the earliest time frame. The National Institutes of Health and the National Cancer Institute have targeted virtual colonoscopy as the pilot study to compare standard video colonoscopy to virtual colonoscopy for screening for colon polyps and cancer. Should this prove effective, virtual endoscopies of any of the other organ systems will follow. There are over 2 million standard video colonoscopic procedures performed each year, and over 75% are "normal", the majority due to screening for cancer. A virtual endoscopic procedure is performed by using a standard CT scan or MRI scan, reconstructing the organ of interest into a 3-D model, and then performing a fly through of the lumen (Figure 3). Typical examples include the colon, stomach, esophagus, tracheo-bronchial tree (bronchoscopy), sinus bladder, ureter and kidneys (cystoscopy), pancreas or biliary tree. There are numerous advantages to such a diagnostic tool, as compared to inserting actual instruments (endoscopes) into the body. First, all endoscopic procedures are invasive, and thus the patient must be sedated and during the procedure they are subject to complications (small though they are) such as perforation, bleeding, etc. The cost for a typical colonoscopy is significant, for it must include a dedicated suite, personnel, specialized equipment, consumable materials, medications and administrative staff. A virtual colonoscopy is constructed from a helical CT Scan of the abdomen, is completely non-invasive and thus without known complications. The actual cost is less than a third of video colonoscopy, since it is performed in the same place and manner as all imaging modalities, utilizes the same staff, and has no consumable materials. The advantages of the video colonoscopy is that a therapeutic procedure can be performed if an abnormality is found, whereas any abnormality on a virtual colonoscopy must be referred for true colonoscopy for the therapy, such as polypectomy or biopsy of suspected cancer. Virtual colonoscopy has the advantage of being able to view the colon from any angle inside the lumen (small polyps can be hidden behind folds or twists in the colon during actual colonoscopy), or being able to fly "outside" of the lumen to see if a tumor has spread to the surrounding tissues or lymph nodes. In addition, the virtual image can be manipulated, actually opening up the tubular structure and lying it flat like a terrain map, to look for abnormalities[13]. The wall thickness can be measured for early flat cancers, not usually detectable by standard colonoscopy. The limitations to virtual colonoscopy at this time are significant, and will need substantial research to reach the full potential. These limitations include accurate color and texture mapping of the tissues. A preliminary step has been taken by John Kerr of Engineering Animation Inc[7], in which a color look-up table has been created using the visible human dataset, comparing Hounsfield units of the CT scan to color values from the phototomographs. The preliminary images, using a liver model, are promising but are not accurate enough to be useful for clinical diagnosis. Just as the early attempts to convert black and white cinema films into colored films have progressed to excellent representations today, advances need to be initiated to create accurate color and texture for endoscopic images. Another limitation is removal of all the stool within the colon to prevent false diagnoses of abnormalities. Solutions under investigation include more effective purgatives, or drinking a fluid which will tag the stool, allowing it to be digitally subtracted during the virtual reconstruction. Finally, the level of resolution of the image today is at 0.3 mm for the helical CT scanners. This is usually adequate for gross lesions, though the full 3-D reconstruction does not give this accuracy. For lesions greater than 3mm in size, there is a 75% detection rate, and those greater than 5 mm have a 95% detection rate[15]. This is becoming comparable to detection rates of standard colonoscopy. As the imaging modalities improve so to will the resolution and detection rate. Perhaps next generation systems will acquire multiple modality (CT, MRI, ultrasound, etc) images, and then using data fusion, provide more information than can be obtained with a single image. The extraordinary challenges of automatic segmentation, registration, accurate tissue identification and data fusion provide nearly unlimited research opportunities which can provide both early and long term benefits for clinical application to patient care.

Another diagnostic application is that of pre-operative planning using the virtual image of patient specific data. There are numerous areas that have had initial investigation, especially in the neurosurgical, orthopedic, maxillo-facial , plastic surgery and vascular arenas. Stereotactic neurosurgery has been clinically implemented for over a decade, and central to the success has been accurate localization of abnormalities in the brain through 3-D reconstructions from CT and MRI scans. Using fiducial markers on the skull or by placement into a frame that provides the stereotactic reference, neurosurgeons have full 3-D models of the brain to precisely plan both the exact position as well as safe pathway to removal or ablation of deep seated brain lesions (Figure 4). The current generation systems are using bony landmarks of the skull as frameless fiducial references for the preoperative model, and then updating the image with real-time open MRI scanning as the stereotactic neurosurgical procedure is being performed[15]. In orthopedic surgery, the areas of hip and knee replacement are maturing as clinical tools. One of the earliest robotic surgical devices, RoboDoc for hip replacement (Figure 5), uses a computer program called OrthoDoc to pre-plan the procedure[16]. Taking orthogonal views of the patient's hip, as well as manufacturer supplied models of the prosthesis, an accurate pre-operative match can be obtained. The coordinates of the placement for the prosthesis are fed into a robotically controlled system to bore out the center of the bone to mount the prosthesis. Normally, a surgeon using hand held surgical instruments can create a cavity into which the prosthesis fits with approximately 75% of the surface contact to the bone. Using RoboDoc, the cavity can be precision crafted so the prosthesis has 96% surface contact, providing a better fitting and longer lasting replacement. Similarly, Anthony DiGioia of Shadyside Hospital in Pittsburg is doing preoperative planning for replacements using HipNav[17]. For maxillo-facial reconstruction of congenital or traumatic abnormalities, Altobelli of Brigham Women's Hospital[18] and recently Montgomery of Stanford University[19] have been using 3-D images from CT scans. The face is a symmetrical structure, so abnormalities on one side of the face or skull have a mirror image portion of the face that is normal. By comparing the normal side of the face to the defect, an accurate reposition or replacement for the malformation can be planned. In the area of defect, the mirror-image model can be exported to a computer assisted design and computer assisted manufacturing (CAD/CAM) system which can precisely manufacture an appropriate prosthesis for implantation and reconstruction. The new generation systems are able to use 3-D stereolithography to automatically construct a 3-D prosthesis directly from the CAD/CAM information. Drs. Steven Pieper and Joseph Rosen of Dartmouth [20] have developed a pre-operative planning tool for plastic surgery reconstruction of skin lesions on the face (Figure 6). Using finite element modeling of the layers of the skin, portions of the skin can be removed and then the results of reapproximating the skin edges using different techniques can be visualized for optimizing the cosmetic appearance. In vascular surgery, Charles Taylor and Chris Zarin of Stanford University[21] have approached the difficult problem of choosing the best vascular grafting for complicated vascular lesions of the aorta and lower extremities. From digital MRI angiography, 3-D repesentation of the vascular tree, the patient specific lesion and fluid dynamics (flow) can be modeled. With this specific anatomy, as well as characteristics of the vascular graft prosthesis, numerous different possibilities for bypassing the specific vascular obstructions can be tried, with each model predicting the probable flow to the lower extremities. The accuracy of these predictive models will soon be validated using animal and clinical trials.

The power of pre-operative planning is analogous to the testing and evaluation through computer simulation in many industrial sectors, from aerodynamics and ergonomics in the aerospace and automobile industries to building structure and interior appearance in the architecture and design fields. The ability to try numerous different possibilities, optimize the procedure for the best choice, and then apply that choice to the patient will significantly increase the quality of healthcare. The question remains as to whether it is cost effective and who will pay for the added expense of the pre-operative planning. Without these computer assisted planning tools, that cost of "planning" an operative procedure is included as the physician's fee, the payment for a surgical procedure includes the surgeon's experience in choosing the best option based upon personal experience. It is uncertain if third-party payers for healthcare will be willing to pay extra for very expensive tests (CT generated 3-D representations) and planning procedures unless the there can be a demonstrated cost savings or long term improved outcomes from the pre-planning of the surgery.

In the area of therapy, virtual environments usually include computer-assisted surgery, image guided surgery and telesurgery because the interface through which the procedure is being performed includes an image of the patient, rather than directly viewing the patient's anatomy. The display is often simply a monitor, however head mounted displays or overlay screens have been also used. In computer assisted surgery, the purpose is to obtain pre-operative planning information which is entered into a computer program, and during the procedure the surgeon is assisted by a robotic device to perform a part of the procedure beyond human physical limitations. An example is RoboDoc mentioned above, with 96% accuracy in prosthesis placement. Telesurgery, or more accurately dexterity enhanced surgery, uses a video monitor with stereoscopic real time video image to enhance the precision and dexterity of the surgeon through direct telemanipulation. Under these circumstances, the surgeon's full attention is upon the virtual image of the patient image, and remote manipulators carry out precisely the hand motions of the surgical task. The system is in the same operating room next to the patient for the purpose of improving the performance of the surgeon (dexterity enhanced surgery), however the procedure could just as easily be at a distant place (telesurgery). The systems are comprised of a remote manipulator system with surgical instruments that are mounted (and can be interchanged) upon the end of a pair of robotic arms. The instruments are placed inside body in the proper position by the surgeon, who then sits at a surgical work station next to the patient and uses input devices (modified handles from surgical instruments) to directly control the end effectors. The systems include force feedback for haptic response, 3-D vision on the monitor for depth perception, scaling of hand motion to increase dexterity and filtering of tremor (at the 8-14 Hz frequency) to increase precision. Research is being conducted to include motion tracking so the system can pace the motion of the beating heart and therefore perform surgery on a beating heart without needing to place the patient on an heart-lung machine while performing the procedure. There have been no remote telesurgery procedures performed upon patients; however two systems have performed the procedures in the same room as the patient. In 1997, Jacques Himpens and Guy Cardier in Brussels, Belgium[21]used the Intuitive Surgical, Inc system to perform the first telesurgery gall bladder operation on a patient. They also performed a number of other procedures, such as Nissen fundoplication and arterio-venous fistula construction. In 1998, Alain Carpentier of Paris France[22] began performing heart operations using this system, and has successfully performed over 150 of the procedures. A second system by Computer Motion, Inc called Zeus is similar to the above system, but focuses more on performing microsurgical procedures (Figure 7). In 1998, Dr. Frank Diamiano[23] performed the first procedure in the United States with a reanastomosis of a fallopian tube using the Zeus system. Both systems are currently undergoing controlled clinical trials on selected patient populations.

Psychiatry and rehabilitation are areas where immersive virtual environments have had important clinical applications. Ralph Lamson of Kaiser Permanente[24] has been using VE for what he calls “virtual therapy” in patients with various forms of phobia. By recreating representations of the Golden Gate bridge or an elevator, people with fear of heights can be deconditioned by repeatedly being exposed in small increments to the virtual threatening environment and allowed to conquer their fears without physical danger to themselves. A similar system has been developed at Georgia Technical Institute by Hodges, et al[25], creating a variety of different environments to test acrophobia and other phobias. After 1 year there is a XX% success, and some of the patients who regress are easily given further virtual therapy and they respond very well. An interesting success has been achieved with a patient with arachnophobia (fear of spiders) by Rothbaum, Weghorst et al at the University of Washington[26] In rehabilitation, Walter Greenleaf[27] has provided a virtual world for wheel chair patients to travel through. By giving the patient ample opportunity to practice without harm to themselves, they can then begin using a wheelchair in a real environment.

An interesting project by David Zeltzer[28] that is beginning is called the Empathy Network. In this project, the concept is to provide the patient's family and loved ones an opportunity to experience the disability which the patient is suffering, such as memory lapses or visual disturbances secondary to minimal brain injury or stroke. A preceding commercial project entitled "In My Steps" which has been successful creates the fatigue which a cancer patient suffers while under chemotherapy[29]. The family member dons a HMD and sits on a stepping machine. The scenario is the patient home (Figure 8), where the patient must prepare a small breakfast while waiting for delivery of important prescriptions. The person must pedal (walk) to the kitchen and put on the tea kettle and toast. By the time they have "walked" to the kitchen, they are fatigued (from the heavy pedaling), and put the kettle on the stove. The door bell rings. Even though they are pedaling hard, their walking progress is extremely slow, and by the time they open the door, the see the prescription delivery truck departing without leaving their medications. At that moment the tea kettle begins whistling, so they must pedal back, and just as they reach the kettle, the toast begins to burn. Of course the person is totally exhausted from the pedaling. There is no empiric data from this project, however the subjective reports have had uniformly high ratings for imparting the sense of fatigue and frustration that their loved ones must be suffering.

Education and training is the largest early application. In the beginning of the 1990's Scott Delp and Joseph Rosen[30] created one of the first VR applications in medicine – a tendon transplant simulator (Figure 9). Using head mounted display (HMD) and DataGlove as the interface, they created a mechanical and anatomic model of the skeleton of the lower limbs which used red lines to represent muscles and tendons. The limbs had mechanical properties and kinematics of the legs, which could be animated to simulate walking. By moving the insertion point of a muscle's tendon to a different point (to plan for a tendon transplant operation to correct a patient with a gait disorder), the model was then animated and the gait observed to predict what the result of the tendon transplant might be. In 1991, Satava and Lanier[31] made the first abdominal simulator (Figure 10), created of simple graphic representations of the liver, stomach, colon, pancreas, gall bladder and biliary tree. Once again, with a HMD and DataGlove, it was possible to fly around the organs and to pick up and move them. A few simple surgical instruments were included, allowing for a very abstract representation of the surgical procedure of removing a gallbladder. By 1993, Jonathan Merrill of HighTechsplanations[32] had added increased graphic realism and introduced morphing to demonstrate changing of tissues in response to interaction. While appearing much more realistic, the deformations were based upon approximations, rather than measurement of properties of actual tissues. The landmark was 1994 with Michael Ackerman[3] from the National Library of Medicine and the release of the Visible Human Project (performed by Drs. Victor Spitzer and David Whitlock[4]). For the first time the visual representation was based upon actual anatomic data from a person, rather than graphic representation of organs and tissues. However the data base is massive, over 15 megabytes, so at the present time it is not possible to render the entire representation in real time interactive simulation. But the Visible Human does provide a standard reference for interoperability of different simulations. The next step was with Scott Delp's Limb Trauma Simulator for the military Combat Casualty Care training program[33]. Taking the upper thigh from the Visible Human and adding to it the properties of muscle, ballistic damage, shrapnel, bleeding and other parameters of wounding, a simulation of a gunshot wound to the thigh was created. The purpose was to provide an alternative to wounding animals for training in combat casualty care. The simulator provides both visual representation of the wound, as well as interactive control of bleeding, debridement and hemostasis using input devices with force feedback for haptic control. However by the time all of the interactive properties have been added, the visual fidelity of the image is reduced to a relative low-resolution representation rather than photorealistic. As computer power increases, virtual representation will eventually have both visual fidelity with physical-based properties derived from scientifically measured tissue and real time interactivity at a minimum of 30 frames per second with a latency of image generation of less than 50 milliseconds. The Limb Trauma Simulator is currently under evaluation at the US Army medical training laboratory of the Uniformed Services University of Health

Sciences (USUHS) by COL Christopher Kauffman[34]. In 1996, Dr. Jeffrey Levy collaborated with Engineering Animation, Inc. to create a hysteroscopy simulator[9]. This system not only integrated visual and haptic input, but the image was derived from patient specific data. Before performing a hysteroscopic procedure on a patient, Dr. Levy imported the image from the patient's CT scan, and was able to practice numerous different procedures to optimize the surgery for that specific patient. By 1998, Marc Raibert constructed the Anastomosis Simulator[35]. In addition to increasing visual fidelity and tissue interaction with haptic input, this system incorporates a testing and evaluation component. The input devices (Phantom Haptic Input Device) which track the precise motion, position, pressure and timing in order to provide the accurate force feedback, also output the information to a graphic display which tracks in real time the student's performance in regard to accuracy, position, pressure and time to completion. At the end of the practice session, a scorecard of the student's performance is tabulated and printed out. This can be used both for real-time feedback for training as well as evaluation for certification. The next step is to provide a curriculum that will support the simulation technology and to develop the metrics for evaluation of performance and outcomes analysis.

There are a number of projects that focus at medical education. Celina Imelinsk at Columbia University[36] has the Vesalius project, which is providing a combination of CD-ROM and web-based virtual environments for pelvic and skull anatomy. Leroy Heinrichs of Stanford University[37] is leading a team to understand pelvic and gynecologic anatomy through VR. Helene Hoffman of University of California, San Diego[38] has a curriculum based upon a virtual representation of the organ systems called the Virtual Reality Multi-media system or VirtualizeR. The module for the biliary tree is complete, with full 3-D hepato-biliary system and interactive links to all the relevant information. For example, while highlighting the gallbladder, the student can access normal and abnormal anatomy, typical patient history and physical exam, histology, pathology, radiologic images, surgical procedures and the full range of information as well as the capability to fly through or practice procedures upon the anatomic representations. The image is the both the educational content and the interface to the information.

Challenges

There remain a number of challenges and barriers to implementing virtual environments more extensively. In all areas, there is the issue of cost and maturity of the systems. Most of the applications are still simplistic, requiring a substantial amount of "suspension of disbelief". The equipment is still rudimentary, from HMD to CAVE to haptic input device. Nearly every system requires a dedicated staff or at least computer technician to keep the system running smoothly. The majority of applications do not have a large number of patients or students for which it is applicable. The following looks at the individual areas and identifies specific challenges.

In order to create image-based medical records (medical avatar), there is the challenge of acquiring enough data non-invasively and automatically inserting it into the database. There is no consensus database, nor are the literally hundreds of databases interoperable. In terms of displaying the information as an image, there are the challenges of automatically segmentation of the CT, MRI, ultrasound images and reconstruction of the 3-D structures, registration of the images accurately, and then data fusion of not only the image data, but embedding the physiologic, biologic and other data to the appropriate source. If the intent is to have an internet-based record, there have been a number of simplistic web based medical records (all of which are incompatible with any other database), however there is no method to automatically download specific data.

There are a number of overarching problems which are non-technical but which have definite possible solutions. One of the largest challenges is coming to an agreement on a standard computerized database (computerized medical record) which can easily and transparently accept all forms of medical information (images, text, data signals, equations, etc) for automatic archiving. It must have a powerful retrieval engine to function as an intuitive interface for access to the information. The next challenge is to agree upon a standard method of displaying the information which is independent of the display device. One suggested possibility is the visual medical record in the form of a medical avatar, which can be viewed on a standard monitor, as a hologram, with a HMD, in a CAVE or with any other device. For universal access to archived data, there appears to be consensus that a web-based medical record can provide a unifying platform, however as in all internet applications there are the issues of security and privacy.

In creating 3-D images for diagnostic purposes, such as virtual endoscopy, the most important and technically difficult barrier is the real-time automatic segmentation of organ systems and tissues. The issue of accurate color and texture to be derived from the acquired images has only been proposed in preliminary demonstration. There is no consensus on the best method of displaying the image. In order to aid radiologists in interpretation, automatic recognition and interpretation by decision support systems needs to be developed. To be able to have a robust diagnostic tool that rivals that of current radiologic standards, the imaging technologies need to improve the resolution of the image significantly, possibly as much as an order of magnitude.

In the therapeutic implementation of telesurgical and dexterity enhancing systems, there remains the issues of latency when attempting to implement at a distance; and for increasing precision and dexterity, improvement is needed in the degrees of freedom of the systems, tracking of position and appropriate scaling of haptics. In all of the systems, although the interface is dramatically better that current laparoscopic systems, they are far from ideal. Some unresolved issues include an automatic initialization and registration of the system before beginning the operative procedure, acceptable hand-eye axis, most appropriate display (HMD, monitor, binocular optical system, etc), tool changing system and method of control for subsystems (voice activated, menu driven, etc).

For the education and training applications, there are the same technical issues listed above for image generation in 3-D visualization in diagnosis (automatic segmentation, registration, etc) as well as the interface issues. In addition the biggest challenges are those of content - of developing an appropriate curriculum which can take advantage of the technology. Of all the applications, education requires that the system be intuitive and easy to use, especially to be usable by students without long periods required simply to learn the system in order to begin studying. The content must be developed in order to have metrics that are able to measure technical skills, and to measure performance in such a way to give meaningful outcomes analysis. To date, none of these metrics have been developed, and until they are derived through consensus and evidence based testing, implementation of the training systems will not be accepted by residency training programs or certification bodies.

Non-technical challenges to the implementation of virtual environments are those which prevent development of the application in spite of the technical feasibility. In implementation of such a diverse set of applications which must be interoperable (such as simulators which can be used on student workstations or be integrated into telepresence surgery systems), the most important factor is standardization. To date none of the various systems are interoperable. An attempt has been made to approach such integration by requiring the 3-D visualization projects to be compatible with the Visible Human dataset. This does not guarantee standardization, however it provides a common reference from which to start. As systems become more complex, the questions of safety and liability apply, as well as certification to use the systems. Not only are the mechanical systems under stringent evaluation from the medical device division of the FDA, but also the computer programs that handle data or control the mechanical devices. Once a device or software program is approved for use, a major challenge is getting the third party payers to reimburse for the cost of a procedures (eg virtual endoscopy) or paying extra for a procedure because more advanced equipment is used, as in image guided or computer assisted surgery. Healthcare insurance companies or managed care organizations resist implementation of a procedure until it can be shown to reduce costs. The current mantra for new technology, whatever the type, is cost-benefit ratio; yet conducting the long-term clinical trials with clearly definable outcomes analysis causes a prolonged delay in payment for a service. On the other hand, a number of new technologies will not be accepted by physicians or patients because of unfamiliarity, conventional prejudice or outright ignorance of the benefits. There is a natural skepticism against anything new and an almost inborn resistance to change. It required almost a new generation of radiologist to accept the new digital images instead of film-based radiology, it is uncertain if it will require decades to accept 3-D visualization and virtual endoscopy. Finally, there are a number of applications which raise serious bioethical and moral issues. Should a psychiatrist subject a patient to a threatening virtual environment that could possibly cause irreversible damage when the capabilities of the state of the art is unknown? Is it permissible for a surgeon to operate upon a patient (using telesurgery) if the surgeon has not met the patient (in a distant city) or is not physically present in the operating room should something goes wrong – are we developing a "tele-itinerant surgeon"? Thus, there are many non-technical hurdles that can impede acceptance of what is otherwise an excellent technical solution to a difficult problem.

Conclusion

This overview has presented numerous specific VR applications which are emerging in the medical field; however the majority are in the laboratory or clinical investigation stage. It will take significant effort to move these technologies into commercial success and therefore routine clinical use. As in many other fields, standardization and interoperability are some of the major issues whose solution will dramatically increase the implementation of the technology. Of all the technical challenges, auto-segmentation, registration and data-fusion are the most difficult but these have the possibility for producing the greatest amount and most rapid acceptance of virtual environments as a clinically useful tool. While it is true that there needs to be orders of magnitude increase in computer power for near realistic visual fidelity, the complexity of the human being is such that there will always be the need for further fidelity, whether on the macroscopic, microscopic or molecular level. Yet the final determinant is the end user; therefore all virtual environments in use today need to become much more user friendly. They must be turn-key solutions that are extremely robust and fault tolerant and which require nearly no technical support or continual maintenance.

The VR applications above provide a framework of what is possible today, and give rise to speculation as to what would be possible by extending the capabilities described. The implications of a 3-D computer generated representation of a specific person (a "digital me") or medical avatar that can act as a surrogate for optimizing (and possibly predicting) individual patient care is extraordinary. Virtual environments are the tools and methodology to create such an interactive information representation, a step in the direction of representing the complexity of human and biologic systems in a manner more clearly understandable and which eventually will be useable and practical for each person. The more devices which are developed that can acquire information about a person (whether hand-held imagers or non-invasive biosensors continuously worn in our clothing or embedded in the body) the richer the medical avatar and the more accurate the results from modeling and simulation, pre-operative planning or intra-operative assistance. Not only is this relevant to patient care for medical conditions, but also to be used at all levels, including school age. Imagine the power of each child having a medical avatar which "grows up" with them, which they carry on a credit card device and use in class. By inserting their avatar into the virtual environment, they can learn health and nutrition by observing the consequences to their avatar. For example, by implementing the "smoking" module, the child's avatar could grow a cancer, get bronchitis and emphysema and decrease the ability of the avatar - as a prediction of what would happen with long term smoking. These types of "what if" scenarios can also be used to engage people into complex intellectual dilemmas, such as bioethical and medical ethical issues of cloning, research on embryos, alternative forms of therapy, etc. Theoretically, if a "generic" or standardized medical avatar could be created, the early phases of clinical trials (on drugs or devices) or virtual "crash dummies" could replace some of the extremely expensive and high-risk testing-and-evaluation occurring today. Other more practical components of VR, such as customizing individual prostheses (or in the not too distant future, creating the model for the instructions to "grow" replacement organs through tissue engineering) by extending the emerging field of medical stereolithography. The applications in psychiatry or virtual therapy are to treat disease; perhaps with insight a virtual environment in the home can be created to ameliorate other disorders before they erupt. There are a number of pragmatic research goals that can be achieved soon by implementing VR for shared experiences, to enrich through high bandwidth communications of Internet 2 a much higher sense of presence with tele-immersion for telemedicine consultations. The ease of use within these virtual environments needs to make the interactivity more transparent, perhaps by increasing the use of voice commands and other intuitive interfaces. It is apparent that there are numerous other directions in diagnosis, therapy and education/training that could be speculated, and the above are listed as examples of technically feasible projects as next steps in the evolutionary process. Yet the medical discipline is unique, in that final result will impact upon a living, breathing human being. The challenge will be to focus upon those applications that can make a quality-of-life difference for each and every patient.

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ILLUSTRATIONS

Figure 1	Suspended holographic image of a mandible (Courtesy of Alan Sullivan, Dimensional Media Associates, New York, NY)
Figure 2	UltraSim, the ultrasound simulator, displays patient derived ultrasound anatomy and pathology on a monitor in response to motions of an actual transducer, precisely mimicking an ultrasound examination (Courtesy of Garrick Herrmann, MediSim Inc., Ft. Lauderdale, FL)
Figure 3.	Virtual colonoscopy (Courtesy of Dr. James Brink, MD , Yale University School of Medicine, New Haven, CT)
Figure 4	Three dimensional representation of a patient with a brain lesion. (Courtesy Dr. James Duncan, Yale University School of Medicine, New Haven, CT)
Figure 5	RoboDoc, precision surgical robot for hip replacement surgery. (Courtesy Dr. William Barger, MD, University California, Davis, Sacramento, CA)
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Figure 10 The IV Insertion Simulator demonstrating high visual fidelity and haptic input on an inexpensive personal computer based platform. (Courtesy Gregory Merrill, HT Medical, Rockville, MD)

Figure 11 Sinus endoscopy simulator provides internal anatomy of the nasal sinuses with overlay of circles that are path planning aids to endoscopic navigation for a surgical procedure. (Courtesy Dr. Charles Edmunds, University of Washington, Seattle WA)

Figure 12. The Anastomosis Simulator incorporates real-time tracking of hand motions by the graph in the upper left corner to give continuous feedback to the student on level of performance. (Courtesy Dr. Marc Raibert, Boston Dynamics, Inc., Boston, MA)

Figure 13 The Anesthesia Simulator is a mannequin based simulator driven by a sophisticated computer program that simulates patient responses, both physically on the mannequin and physiologically in response to anesthesia procedures. (Courtesy of Garrick Herrmann, MediSim Inc., Ft. Lauderdale, FL)

Figure 14 The Ophthamology Simulator uses an operating microscope, a haptic input device, and a virtual representation of the eye. (Courtesy Dr. John Peifer, Georgia Technical Institute, Atlanta, GA)

Figure 15

Figure 16 Shoulder Arthroscopy simulator includes online educational resources (Courtesy Robert Poole, Prosalvia, Inc. New York, NY)

Figure 17 Knee Arthroscopy simulator with mannequin leg and high fidelity internal knee anatomy (Courtesy Dr. Marc Raibert, Boston Dynamics, Inc., Boston, MA)

Medical Applications of Virtual Reality

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  B. 3-D visualization, VR and the framework of the future of medicine
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