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Virtual Reality and Surgery

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I. Introduction

Virtual reality (VR) encompasses a number of surgical research topics, including computer graphics, imaging, visualization, simulation, data fusion, and telemedicine. In this chapter we define VR and each of these areas, focusing on a state-of-the-art review of the research and recent accomplishments. However, first we provide an overview vision of this field and a research agenda to reach it.

This vision comes from work done by Robert Mann in the 1960s (1). We can imagine a patient undergoing a complex operation such as a joint replacement. The surgeon needs to choose from several approaches, a number of different prostheses, and a number of postoperative rehab protocols. The surgeon would like to select each of these choices of treatment and among the various outcomes choose the best for the patient. In reality the surgeon can only select one course.

Mann's vision was to create a virtual patient-specific model of the patient and the procedures, prostheses, and rehab protocols. The physician could then review several different alternatives in a virtual environment. The virtual model would undergo rehab over a 2-year period and would then be assessed to determine what was the best outcome. Once this was accomplished, the surgeon could choose which complex procedure should be performed in reality and carry it out (2). The first steps towards this vision have been realized, especially over the past 10 years in several areas at a number of institutions. Further research in surgery needs to be done in a number of areas, as will be described below.

To accomplish the above goal requires development of a patient model of the actual patient in need of the procedure. The model needs to be "accurate" in a number of ways, including anatomy and physiology. The virtual model not only needs to be accurate with respect to normal anatomy but needs to model the pathology as well. If the patient has degenerative knee joint disease, this needs to be included with regard to effects on muscle function, ligaments, cartilage, and the patient's ability to walk. More difficult is the ability to predict wound healing and subsequent rehabilitation. This involves not just the musculoskeletal system, but it also involves a model that assesses higher functions. There already exist software approaches that simulate some of these aspects, but more modeling approaches need to be developed to better predict mathematically the outcomes and to integrate a number of varying models into one overall master system for the patient. This is similar to what Boeing did using computers to simulate and test completely all of the systems for their new 777 (3). Building all of the parts of a truly realistic virtual medical model still entails much research and experimentation.

As the human virtual model in all its dimensionality is developed, several other areas need further development. These include the tools to interact with the model and the environment, and the ability to overlay the model on the real patient. Finally, there is also an interest in doing all of this at a distance in special cases (telesurgery).

Within the virtual environment where the model exists, a virtual operating room would be created. This operating room should in some cases allow the surgeon to perform the procedure and "see" and "touch" the virtual human. Although this is now possible, the resolution of both of these senses is still limited. The vision component is being actively addressed in other industrial fields, but the detail required in "touch" is more unique to surgery. Force feedback, or haptics, requires machines that use the information from the virtual patient model and transform it into a realistic touch for the surgeon. These instruments have improved recently, but still lack the resolution needed for a surgeon to experience fully and learn from operating in a virtual world. The virtual environment as an operating room can be approached through several "portals." These are usually visual with the addition of haptic devices, all of which at present still lack the ability to provide the fully immersive experience that should be our goal. Each of these approaches will be discussed further below.

When coupling the virtual model to the real patient, invariably a mismatch occurs between the real patient at the time of operation and the patient virtual model. This registration of the real and the virtual is more complex than it first appears. More innovative methods need to be developed to perform this superimposition. Finally, as we attempt to perform telesurgery we must develop solutions for the delays that occur as we move further away from the real patient. There are a number of approaches being developed to address this issue.

II. Definitions and Background

Virtual reality is the use of a computer interface to simulate, in a synthetic environment, a real or imaginary world, through the computer operator's senses (2). These are most commonly visual, tactile (haptic), or auditory senses and allow for an interactive, virtual environment. The terms *virtual reality*, *synthetic environment*, and *virtual environment* are often used interchangeably. The historic ancestors of VR are the flight simulator and the popular videogames (4).

Flight simulators are cost-effective and proved means to train pilots and maintain pilot skills. This technology is now aiding medicine and surgery to train and assess professional medical skills (5). There has been mounting concern that traditional continuing medical education (CME) courses that utilize didactic lectures do not improve physician performance. Interactive CME alone, or combined with didactic instruction, allows an opportunity to practice skills and can change physician performance (6). A review of the literature shows that small group discussions, interactive videos, and simulated patient encounters have been employed. VR has potential to become the natural progression of these methods for teaching and CME.

VR is predicted to very soon play a critical role in credentialing surgeons (7, 8). With its power to allow training and testing in any procedure, it will serve as an objective tool to measure competence, just as it is used in the airline industry. It will offer the additional advantage of avoiding the use of animal models or patients to improve surgical skills (9). VR for teaching and credentialing is an important area for further research.

In the following discussions we explore three-dimensional (3D), multidimensional, and multiuser virtual human modeling applications. We then look to virtual environment representation. The use of virtual tools and manipulation in surgical simulators will also be reviewed. The use of augmented reality to benefit surgical planning and procedures and the roles that telesurgery and cybersurgery may play in the coming years are then examined.

III. Surgical Simulators

Surgical simulators require three fundamental needs to be met (10). The first is a virtual human model. Classical anatomy, ultrasonography (USG), computer tomography (CT), and magnetic resonance imaging (MRI) provide two-dimensional imaging, which may be manipulated by volumetric mathematical computerization to provide detailed 3D imaging, (see Fig. 1). A fourth or multiple dimension may be added with further overlaid information showing function (e.g., liver function tests), time (future growth), predicted healing, operative parameters (blood loss), and so forth. The second requirement is for virtual instrumentation and tracking to perform surgical procedures. This involves solving tactile feedback for incising tissues and detecting abnormal tissue. The third requirement is a virtual environment that can be shown to be effective in training and cost, and is

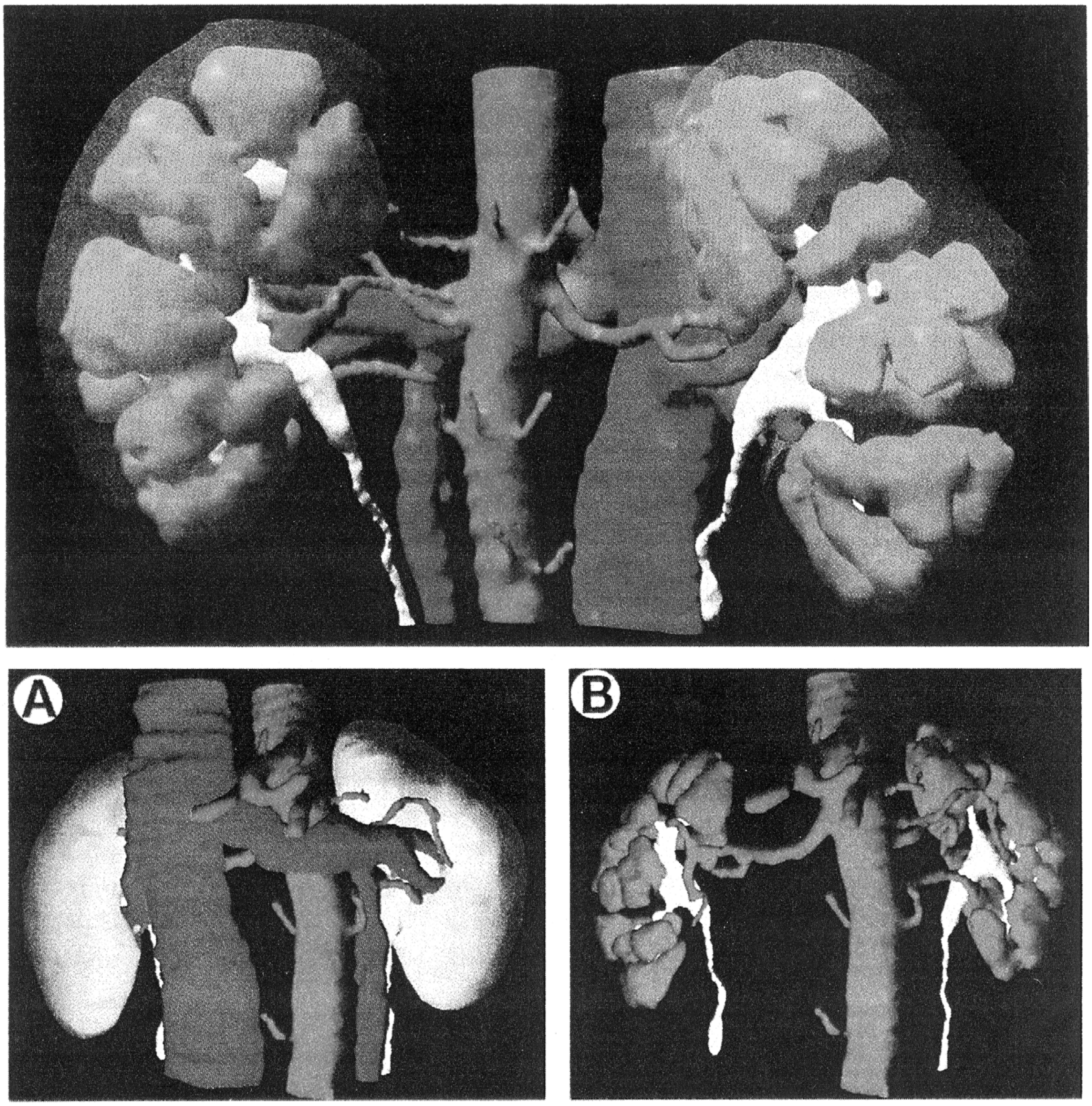

Figure 1 An anterior view of a 3D reconstruction of the kidney using contrast-enhanced spiral CT data. Courtesy of Lori Lerner. (See color plates.)

accepted by users, in terms of comfort and convenience (user friendliness). A virtual environment system consists of the operator, the machine (display) interface, and the computer simulator. A measure of the success of the VR is the degree of sense of being completely immersed within the computer representation.

A. General Approaches

The National Library of Medicine (NLM) at the National Institutes of Health (NIH) sponsored The Visible Human Project to create complete, anatomically detailed, three-dimensional representations of the normal male and female human bodies (see the NIH web site at www.nlm.nih.gov/research/visible). Transverse CT and MRI cryosection images were acquired; the male cadaver was sectioned at 1-mm intervals and the female cadaver was sectioned at 0.33-mm intervals. The Visible Human Project transparently linked visual knowledge forms to symbolic knowledge formats such as the names of body parts (11, 12). These data in turn have been incorporated into various projects, both on the web through links at the NIH site and into the leg bullet wound simulator discussed below.

The VR human model requires accurate patient-specific data to be mapped to the tissue, organ, system, and body region from CT, MRI, and ultrasound imaging. This requires volumetric encoding with reference to an absolute reference frame independent of and exterior to the patient. Mathematical algorithms can be employed to define a finite element mesh (FEM). The FEM allows each point in the VR human to be defined into elements that can be grouped with other points to approximate a tissue or organ and its behavior or its relationship to adjacent elements, for example, skin, muscle, fascia, bone, and organs. This allows a computer to model how a distortion of one set of elements will affect a second—for example, a simulation may predict how lower extremity tendon transfer operations will affect ambulating. How tissues and organ systems behave over time is a future research question (13).

Virtual tools primarily are for seeing and touching, though hearing may be useful as a primary sense, or substituted as an aid for virtual seeing and touching (sonar to find an embedded tumor). Head-mounted displays (HMDs) allow a screen to be placed before an operator's eyes. These displays stem from research done by NASA, and their resolution is currently approaching TV image quality (14). Screens may also be placed on the patient or suspended in front of the surgeon. Virtual retinal display focuses a fine beam of light onto the retina. Further development of this lightweight technology is needed to improve resolution and to broaden the imaging to the entire retina. The University of Illinois has developed the CAVE system where by 3D images are projected within an 8-ft^3 room, allowing physicians to walk between images (for example, neurons from a brain biopsy). Holographic imaging is another area of investigation (14).

The sense of touch includes proprioception, vibration, temperature, kinesthesia, texture, and light and heavy pressure. Haptic input devices currently in use primarily sense pressure. By the resistance, which a probe generates via joystick-type or glove-based devices, a surgeon "feels" contact with different tissues. Current systems, including the Massachusetts Institute of Technology (MIT) Newman Laboratory joystick or the PHANToM interface used by MusculoGraphics Inc., simulate forces on an instrument held in the user's hand (15). However, translating texture is presently a research challenge. A microelectromechanical system (MEMS) employs computer chip fabrication technology and mechanical components to create miniature sensors for pressure, acceleration, and fluid flow. By combining computer chip technology with sensors and actuators, the MEMS promises future progress as more mechanical functions are matched to advances in mirocomputing; this technology is expected to impact future haptic research (16).

Instrument tracking may be done with real-time imaging and processing (fluoroscopy, USG) or may be done with attached sensors. Optical, electromagnetic, ultrasonic sensors can provide continuous spatial localization. Current research is developing a virtual operating tray from which a surgeon can choose virtual instruments, which then may be manipulated to repair soft tissue and bone trauma (17). The instruments actually handling the tissue must have dexterity, force, and precision; they must also give quality sensory output that can reach the surgeon's hands. Daum is investigating the use of a three-fingered grasper that can be controlled by a glove device. Other investigators are using shape memory allow materials to increase the dexterity of the instruments (13). Tactile sensors may be placed in the tips to provide force feedback pressure.

As an example of existing applications of virtual reality simulation, McKenna has developed a biomechanical model and simulator (see Fig. 2) to generate stable standing posture, rising on the toes, and arm movement to reach objects, using a 90-degrees-of-freedom algorithm (18). Using a high-end computer workstation and the Copus computer program, simulation times range from real-time for simplified models to approximately half an hour for complex models. Future research could expand the degrees of freedom to 142 to include all 136 joints found in humans. Importing patient-specific information for surgical planning is a future research goal. Better modeling of the soft tissue components could create a highly sophisticated human figure model.

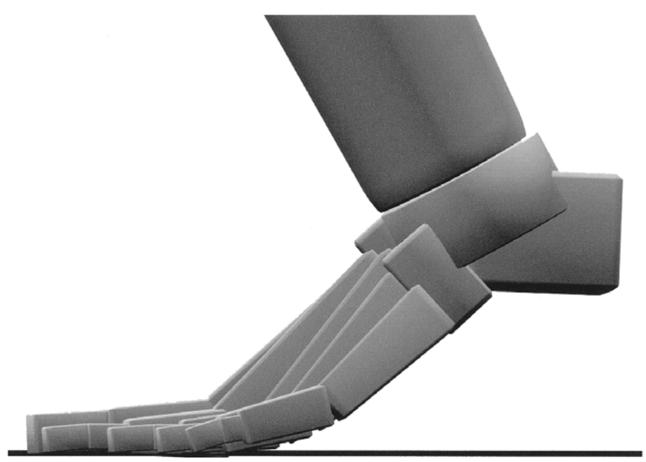

Figure 2 An image of McKenna's fully articulated simulation of the foot. Courtesy of Mike McKenna.

Another simulation predicts the path of a bullet wound through the thigh and the resulting soft tissue injury (Fig. 3) (19). The model accounts for the cylindrical entrance wound, the bullet's breakup into four fragments on striking the femur, the deflection of bone and bullet fragments, and the resulting soft tissue injuries. Future work may more accurately calculate the sizes and positions of the bone fragments from the bullet's parameters. Current imaging resolution is less than that for the virtual human to allow the computer to simulate bleeding, wounding, and instrument interaction. The program can predict functional consequences for the musculoskeletal and circulatory systems and the patient's ability to walk after healing. The circulatory model predicts blood loss, heart rate, and cardiac output as the wound is repaired. These are complex situations to simulate and the model simplifies some functions, which may eventually be incorporated for better accuracy. The purpose of this simulator is to train combat physicians and the application has become part of the training at Special Operations Command Medical Training Center, Ft. Bragg, NC. This type of virtual reality simulator replaces the traditional animal model wound study, a distinct advantage (19).

Endoscopic simulators have been developed for hysteroscopy using a haptic device for hysteroscopic instruments and imported patient-specific anatomy and pathology, allowing surgeons to practice virtual pathology before operating on real patients (35). VR bronchoscopy and colonoscopy using CT, MRI, or USG results in 3D images comparable to videoendoscopy. Future applications can explore areas not accessible to endoscopes, such as the inner ear and celiac ganglion. Satava has created a virtual abdomen that can teach anatomy and operative procedures (20). The user can virtually fly through the organs and systems from the inside and experience anatomical relationships.

Currently, it is too difficult to simulate the complexity of an entire surgical procedure. The future of VR for training and testing has been proposed to start with studying expert surgeons, to analyze and categorize surgical procedures as defined sets of skills and knowledge, tasks and subtasks, the routine and extraordinary, successful and unsuccessful outcomes. VR can make this lifelike, variable, and real time to be realistic. Key elements and tasks could then be targeted and addressed with VR applications. How to best employ VR in this setting is an important question.

B. Representations

Virtual colonoscopy (VC) has been shown to have similar efficacy as conventional colonoscopy (CC) for detecting polyps 6 mm or more in diameter (21). VC uses a helical (spiral) CT scanner to generate images at 2-mm intervals, with a 3-mm slice overlap, with the patient in both the prone

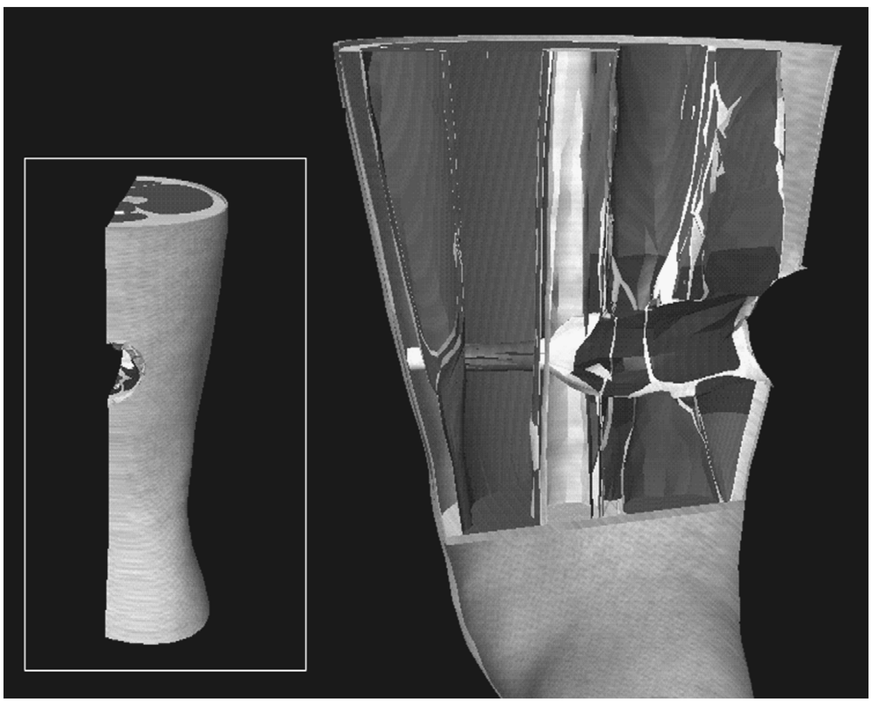

Figure 3 A simulated model of tissue damage caused from cavitation caused by the entry of a high-velocity bullet into the human thigh. Combined with surgical simulation programs, this system is used for wound trauma training. Courtesy of MusculoGraphics Inc., Evanston, IL.

and supine positions. The patient has undergone a very thorough bowel preparation, has had the colon inflated to the maximum level of tolerance, and has an injection of glucagon to minimize smooth-muscle spasm and peristalsis. A radiologist then examines the VC at a computer workstation, using 3D software (www.cs.sunysb.edu/vislab/projects/colonoscopy/colonoscopy.html). It has been pointed out that these are promising results but that more work needs to show that this can replace CC or a barium enema for screening purposes. It remains technically challenging and time-consuming for study review. Sessile 1-cm polyps are regularly missed in the right colon, and because of the gas insufflation, patients may rate CC as more comfortable than VC. This study raises some technical questions, but the most fundamental question concerns whether the viewing process be computerized to find lesions for the physician to then study. This application may also eventually be helpful for VR spiral CT chest screening (22).

One commonly asked question is whether we can afford this new technology or how it can be justifiably used. Although VC may not yet be affordable when compared to conventional treatment, one new VR application does claim to be both cost-effective and clinically better. How does a surgeon decide which kidney to harvest when a patient donates a kidney (23)? Living renal donor transplantation normally requires renal arteriography and, at some institutions, excretory urography (IVP) to evaluate renal function and anatomy. Medical Media Systems has developed computer software to take helical CT scanner data and, with color coding of structures by trained biomedical engineers, construct 3D, multiplanar reformatted images (24) (Fig. 4). Within 72 hr, a floppy disk is available for the surgeon to view the kidneys, ureters, and arterial and venous structures in beautiful, bright colors.

Conventional angiography has a complication rate of 1.4% and includes arterial dissection, thrombosis, groin hematoma, bleeding, contrast reactions, contrast-induced renal failure, angina, and (rarely) neurological injuries. In comparison, CT rarely leads to complications such as contrast reactions. In addition, angiography has been reported to miss up to 8% of living donor vessels and poorly visualizes venous vasculature, whereas 3D modeling of 20 patients did not miss any arterial vasculature, identified plaques and calcifications, and accurately portrayed venous

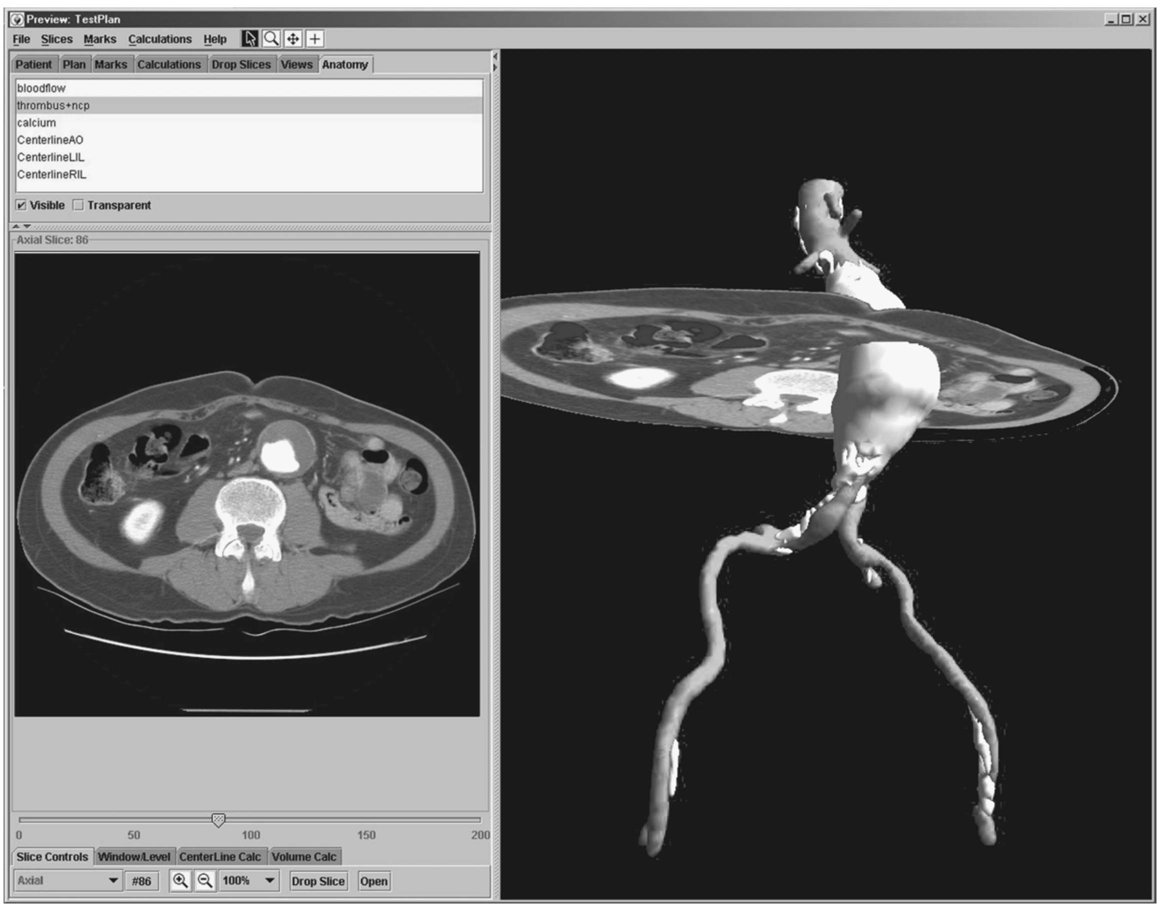

Figure 4 An image from the Preview application by Medical Media Systems. The three-dimensional, patient-specific image is useful to the surgeon in both planning surgery and targeting. Courtesy of Medical Media Systems, West Lebanon, NH.

vasculature. The cost for the VR study is $450 for the CT and 3D imaging, a substantial savings compared to angiography and IVP (25).

IV. Augmented Reality

Augmented reality (AR) systems superimpose virtual information over real structures (Fig. 5). Goggles allow CT, MRI, or USG display of patient-specific data while the surgeon is viewing the patient's abdomen, for example. It has been used to view a pregnant woman's fetus in a 3D manner prior to operation. Novice surgeons may have difficulty visualizing organs in 3D. AR enables viewing the anatomy in 3D to help master this knowledge faster (36). An AR system for neurosurgeons allows for CT or MRI imaging of a brain tumor to be transformed into a 3D image, which is then superimposed on the patient's head to help plan the skin incision and bone flap approach. The surgeons may then use the program in the operating room as a reference map to help assess the surgical margins.

Computer-aided plastic surgery (CAPS) uses a 3D model of the human face with a FEM overlaying soft tissue to estimate the results of tissue ablation and rearrangement (Fig. 6). CAPS allows a surgeon to simulate and plan facial surgery. The FEM technology allows volumetric remodeling after removing or relocating soft tissue, this essential feature of CAPS begins with a videoscan of the face, yielding cylindrical coordinates and documenting skin color. CAPS then translates the cylindrical coordinates into rectangular coordinates, allowing the viewer to manipulate the image from any outside point (26–32). The surgeon uses a mouse to make incisions, flaps, remove tissue, and so forth. The computer then segments the face into triangular or quadrilateral facets, incorporating the incisions as edges. The user designates simple approximation or a double Z-plasty rhomboid-to-W closure. A skin stiffness matrix is referenced to integrate the strain and distortion this reconstruction produces on the skin soft tissue. An algorithm for the displacement data then constructs the CAPS-predicted outcome (31).

V. Robotic Employment of Virtual Reality

Hip replacement surgery has traditionally been planned by overlaying templates on X-ray views to select implant type and size (33). ORTHODOC is a computer workstation that takes a special CT of the hip, after implanting three bone screw reference points; this helps the surgeon plan the operation in 3D. The ROBODOC operation is then performed with ORTHODOC, giving cutting instructions to the robot to form the cavity, using the screws as reference points. The surgeon may stop the robot at any time and revert to customary procedure because the operative field is fully exposed (33).

Robotically assisted heart bypass surgery, using the ZEUS Robotic Surgical System, is undergoing U.S. Food and Drug Administration (FDA)-approved Investigational Device Exemption (IDE) clinical trials. This system enables the surgeon to perform critical suturing through small pencil-sized ports. An endoscope is inserted into the chest and positioned by a voice-controlled robotic arm. While seated

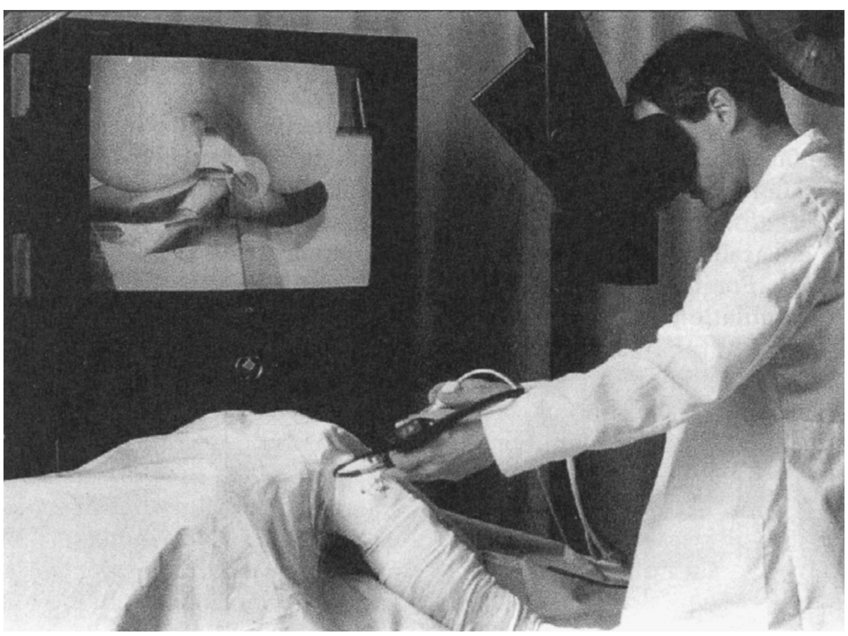

Figure 5 Data fusion by augmented reality.

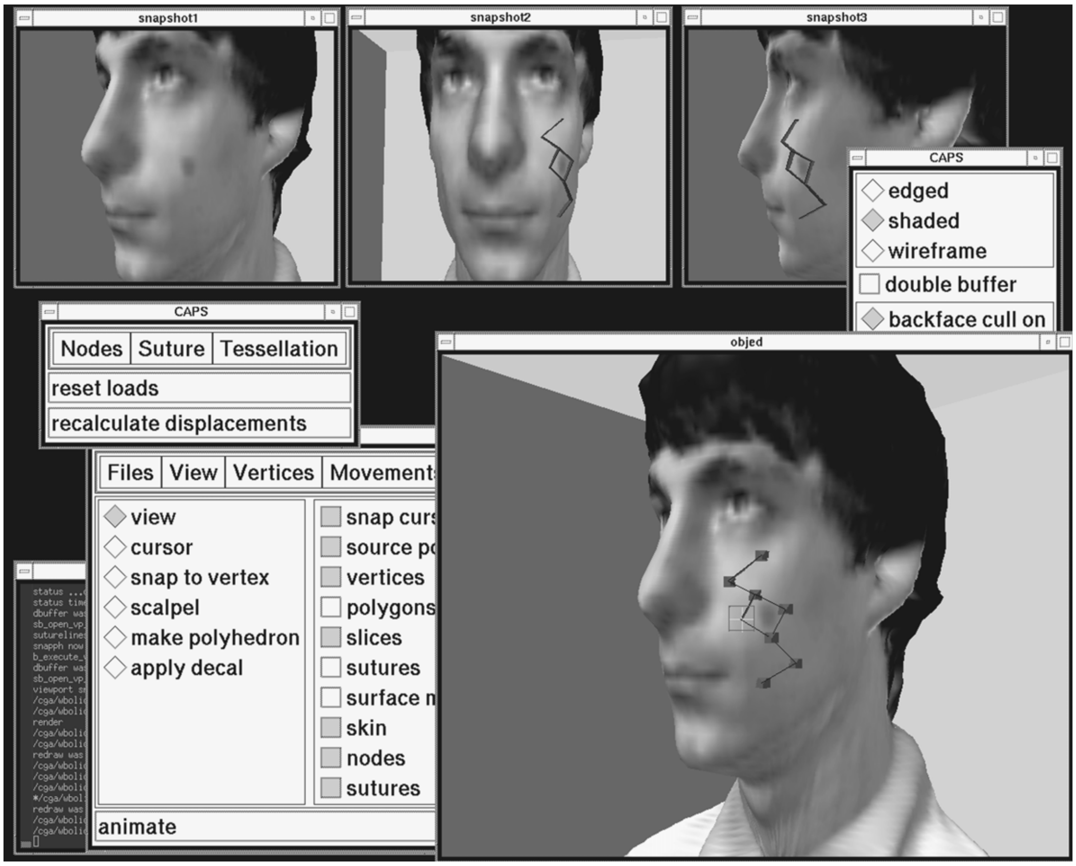

Figure 6 An image from the Computer-Aided Plastic Surgery Program (CAPS) developed to assist the physician in presurgical planning. It allows the surgeon to try a number of approaches before entering the operating room, which is especially useful when aesthetics is a crucial factor, such as this situation in which a small lesion is being removed from the patient's cheek. From Ref. (31), S.D. Peiper, D.R. Laub, Jr., and J.M. Rosen (1995). A finite-element facial model for simulating plastic surgery. *Plast. Reconstr. Surg.* **96**, 1100–1105.

at the console, the surgeon can view the operative site in either 3D or 2D, depending on preference. Movements of the surgical instruments are controlled via handles that resemble conventional surgical instruments. These movements of the handles are scaled, and tremor is filtered to enhance surgical precision (34)

VI. Telesurgery

By using electronic information and communication technologies, surgeons can practice at a distance from a patient (13). A surgeon may telementor a student, to train and educate, or teleproctor an experienced practitioner, to evaluate and certify skills. These techniques have been successfully applied to laparoscopic hernia repairs and other teaching situations. However, questions have been raised about licensing requirements for recipient practitioners of electronically transmitted medical technology. Other concerns include the need for backup plans in the event of communication breakdown, and proper preparation prior to surgery (adequate review of medical documentation and treatment discussion). Wire transmission over 200 miles and wireless transmission greater than 50 km are the limits to performing telesurgery, due to lag-time problems and effects on coordination (telepresence). Satellite transmission cannot be used for this reason.

Telesurgery is a natural extension of the skills younger physicians have learned playing videogames, which requires decoupling of the oculo–vestibular axis from the tactile–proprioceptive axis to manipulate the game consoles. Telepresence surgery attempts to transform the remote feeling of laparoscopic surgery into the more natural feeling of open surgery. With the SRI system (SRI International, Menlo Park, CA), the surgeon views a 3D image from a minimally invasive procedure, which portrays organs and instruments as if the operative field was fully open. The surgeon sits at a console, inside or outside the operating suite, while an assistant stays with the patient, and receives tactile feedback from the instrument tips.

Using this technology the following procedures have been demonstrated with animals: gastrostomy and closure, gastric resection, bowel anastomosis, liver laceration suture, liver lobe resection, splenectomy, aortic graft replacement, and arteriotomy repair (13).

Technology can compensate for human limitations of hand positioning (200 μm), intention tremor, and eye saccade motion (13). The Hunter telepresence system for opthalmological surgery tracks the motion of the eye. It increases instrument scale such that 1 cm of hand motion equals 10 μm of laser movement. Videoimages magnify retina vessels to the size of fingers. Digital signal processing and filtering remove hand tremor. By using these techniques, the limits of human accuracy are improved from 200 to 10 μm.

VII. Conclusions and Future Research

The critical steps toward realizing the promise of virtual reality in surgery involve continued significant development in the fields of human models, interface devices, and system verification. Human modeling by far poses the greatest challenge and will require several generations of improved computer mathematical algorithms to achieve accurate representation of normal humans and pathologic conditions. This is especially true for predicting changes over time (e.g., aging and outcomes). The second critical component, haptic or visual interface tools, will continue to evolve with the help of many industries (e.g., defense contractors) that also benefit from improving this technology. The third requirement, system verification, is key to the acceptance of VR by practicing surgeons and consists of two components. The first is scientific demonstration of how well virtual reality systems provide the "touch" and "feel" of true reality. Second, we will need to prove that a training experience in a virtual reality simulator translates into actual improvement in the performance of the clinician. Just as the incorporation and acceptance of flight simulators in pilot training took many years, a serious, long-term research effort will be necessary before the tools and interfaces of virtual reality become an integral dimension of surgery. The future of VR is exciting and its benefits will soon be within our grasp.

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