The Virtual Surgeon: New Practices for an Age of Medialization

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Surgery is experiencing rapid change in its culture, institutions, and material practices due to what we might best characterize as an accelerating technological revolution in medialization. Media inscribe our situation. We are becoming immersed in a growing repertoire of computer-based media for creating, distributing and interacting with digitized versions of the world, media that constitute the instrumentarium of a new epistemic regime. In numerous areas of our daily activities, we are witnessing a drive toward fusion of digital and physical reality; not the replacement of the real by a hyperreal, the obliteration of a referent and its replacement by a model without origin or reality as Baudillard predicted, but a new playing field of ubiquitous computing in which wearable computers, independent computational agent-artifacts, and material objects are all part of the landscape. To paraphrase William Gibson's character Case in *Neuromancer*, "data is being made flesh."

Surgery provides a dramatic example of a field newly saturated with information technologies. In the past decade computers have entered the operating room to assist physicians in realizing a dream they've pursued ever since Claude Bernard: to make medicine both experimental and predictive. The emerging field of computer-assisted surgery offers a dramatic change from the days of individual heroic surgeons. Soon surgeons will no longer boldly improvise modestly preplanned scripts, adjusting them in the operating room to fit the peculiar case at hand. Increasingly, to perform surgery surgeons must use extensive 3D modeling tools to generate a predictive model, the basis for a simulation that will become a software surgical interface. This interface will guide the surgeon in performing the procedure.

The Minimally Invasive Surgery Revolution

These developments in surgery date back to the 1970s when the first widely successful endoscopic devices appeared. First among these were arthroscopes for orthopedic surgery, available in most large hospitals by 1975, but at that point more a gimmick than a mainstream procedure. Safe surgical procedures with such scopes were limited because the surgeon had to operate while holding the scope in one hand and a single instrument in the other.

What changed the image of endoscopy in the mind of the surgical community and turned arthroscopy, cholecystectomy—removal of the gallbladder with instruments inserted through the abdominal wall—and numerous other endoscopic surgical techniques into common operative procedures? The introduction of the small medical video camera attachable to the eyepiece of the arthroscope or laparascope was a first major step. French surgeons were the first to develop small, sterilizable high-resolution video cameras that could be attached to a laparoscopic device. With the further addition of halogen high intensity light sources with fiber optic connections, surgeons were able to obtain bright, magnified images that could be viewed by all members of the surgical team on a video monitor rather than just by the surgeon alone. This technical development had consequences for the culture of surgery; it contributed to greater cooperative teamwork and opened the possibility for surgical procedures of increasing complexity, including suturing and surgical reconstruction done only with videoendoscopic vision.[1] French surgeons performed the first laparoscopic cholecystectomy in 1989. A burgeoning biomedical devices industry sprang up almost immediately to begin providing the necessary ancillary technology to make laparoscopic procedures practical in your local hospital, such as new, specialized instruments for tissue handling, cutting, hemostasis, and many more.

Due to their benefits of small scars, less pain, and a more rapid recovery, endoscopic procedures were rapidly adopted after the late 1980s and became a standard method for nearly every area of surgery in the 1990s. Demand from patients has had much to do with the rapid evolution of the technology. Equally important have been the efforts of health care organizations to control costs. In a period of deep concern about skyrocketing healthcare costs, any procedure that improved surgical outcomes and reduced hospital stays interested medical instrument makers. Encouraged by the success of the new videoendoscopic devices, medical instrument companies in the early 1990s foresaw a new field of minimally invasive diagnostic and surgical tools. Surgery was about to enter a technology-intense era that offered immense opportunities to companies teaming surgeons and engineers to apply the latest developments in robotics, imaging, and sensing to the field of minimally invasive surgery. While path breaking developments had occurred, the instruments available for such surgeries allowed only a limited number of the complex functions demanded by the surgeon. Surgeons needed better visualization, finer manipulators, and new types of remote sensors, and they needed these tools integrated into a complete system.

Telepresence Surgery

A new vision emerged, heavily nurtured by funds from the Advanced Research Projects Agency (ARPA), the NIH, and NASA, and developed through contracts made by these agencies to laboratories such as Stanford Research Institute (SRI), Johns Hopkins Institute for Information Enhanced Medicine, University of North Carolina Computer Science Department, the University of Washington Human Interface Technology Laboratory, the Mayo Clinic, and the MIT Artificial Intelligence Laboratory. The vision promoted by Dr. Richard Satava, who spearheaded the ARPA program, was to develop "telepresence" workstations that would allow surgeons to perform telerobotically complex surgical procedures that demand great dexterity. These workstations would recreate and magnify all of the motor, visual, and sensory sensations of the surgeon as if he were he actually inside the patient. The aim of the programs sponsored by these agencies was eventually to enable surgeons to perform surgeries, such as certain complex brain surgeries or heart operations not even possible in the early 1990s, improve the speed and surety of existing procedures, and reduce the number of people in the surgical team. Central to this program was telepresence-telerobotics, allowing an operator the complex sensory feedback and motor control he would have if he were actually at the work site, carrying out the operation with his own hands. The goal of telepresence was to project full motor and sensory capabilities—visual, tactile, force, auditory—into even microscopic environments to perform operations that demand fine dexterity and hand-eye coordination.

Philip Green led a team at SRI that assembled the first working model of a telepresence surgery system in 1991, and with funding from the NIH Green went on to design and build a demonstration system. The proposal contained the diagram shown in Fig. 1,[2] showing the concept of workstation, viewing arrangement, and manipulation configuration used in the surgical telepresence systems today. In 1992 SRI obtained funding for a second-generation telepresence system for emergency surgeries in battlefield situations. For this second-generation system the SRI team developed the precise servo-mechanics, force-feedback, 3D visualization and surgical instruments needed to build a computer-driven system that could accurately reproduce a surgeon's hand motions with remote surgical instruments having 5-degrees of freedom and extremely sensitive tactile response.

[Figure # Philip Green, Force Reflecting Surgical Manipulator, Time Magazine, 1996]

In late 1995 SRI licensed this technology to Intuitive Surgical, Inc. of Mountain View, CA. Intuitive Surgical furthered the work begun at SRI by improving on the precise control of the surgical instruments, adding a new invention, EndoWrist™, patented by company cofounder Frederic Moll, which added two degrees of freedom to the SRI device—inner pitch and inner yaw (Inner pitch is the motion a wrist performs to knock on a door; inner yaw is the side-to-side movement used in wiping a table)—allowing the system to better mimic a surgeon's actions; it gives the robot ability to reach around, beyond and behind delicate body structures, delivering these angles right at the surgical site. Through licenses of IBM patents, Intuitive also improved the 3D video imaging, navigation and registration of the video image to the spatial frame in which the robot operates. The system employs 250 megaflops of parallel processing power.

A further crucial improvement to the system was brought by Kenneth Salisbury from the MIT Artificial Intelligence Laboratory who imported ideas from the force-reflecting haptic feedback system he and Thomas Massie invented as the basis of their PHANToM™[3] system, a device invented in 1993 permitting touch interactions between human users and remote virtual and physical environments. The PHANTOM™ is a desktop device which provides a force-reflecting interface between a human user and a computer. Users connect to the mechanism by simply inserting their index finger into a thimble. The PHANTOM™ tracks the motion of the user’s finger tip and can actively exert an external force on the finger, creating compelling illusions of interaction with solid physical objects. A stylus can be substituted for the thimble and users can feel the tip of the stylus touch virtual surfaces. The haptic interface allows the system to go beyond previous instruments for minimally invasive surgery (MIS). These earlier instruments precluded a sense of touch or feeling for the surgeon; the PHANToM™ haptic interface, by contrast, gives an additional element of immersion. When the arm encounters resistance inside the patient, that resistance is transmitted back to the console, where the surgeon can feel it. When the thimble hits a position corresponding to the surface of a virtual object in the computer, three motors generate forces on the thimble that imitate the feel of the object. The PHANToM™ can duplicate all sorts of textures, including coarse, slippery, spongy, or even sticky surfaces. It also reproduces friction. And if two PHANToM™s are put together a user can 'grab' a virtual object with thumb and forefinger. Given advanced haptic and visual feedback, the system greatly facilitates dissecting, cutting, suturing and other surgical procedures, even those on very small structures, by giving the doctor inches to move in order to cut millimeters. Furthermore, it can be programmed to compensate for error and natural hand tremors that would otherwise negatively affect MIS technique.

The surgical manipulator made its first public debut in actual surgery in May of 1998. From May through December 1998 Professor Alain Carpentier and Dr. Didier Loulmet of the Broussais Hospital in Paris performed six open heart surgeries using the Intuitive™ system.[4] In June of 1998 the same team performed the world's first closed-chest video-endoscopic coronary bypass surgery completely through small (1-cm) ports in the chest wall. Since that time more than 250 heart surgeries and 150 completely video-endoscopic surgeries have been performed with the system. The system was given approval to be sold throughout the European Community in January of 1999.

Computer Modeling and Predictive Medicine

A development of equal importance to the contribution of computers in the MIS revolution has been the application of computer modeling, simulation, and virtual reality to surgery. The development of various modes of digital imaging in the 1970s, such as CT (which was especially useful for bone), MRI (useful for soft tissue), ultrasound and later PET scanning have made it possible to do precise quantitative modeling and preoperative planning of many types of surgery. Because these modalities, particularly CT and MRI, produce 2D "slices" through the patient, the natural next step (taken by Gabor Herman and his associates in 1977) was to stack these slices in a computer program to produce a 3D visualization.[5] Three dimensional modeling first developed in craniofacial surgery because it focussed on bone, and CT scanning was more highly evolved. Another reason was that in contrast to many areas of surgery where a series of 2D slices—the outline of a tumor for example—give the surgeon all the information he needs, in craniofacial surgery the surgeon must focus on the skull in its entirety rather than on small sections at a time.

Jeffrey March and Michael Vannier at the Washington University in St. Louis pioneered in the application of 3D computer imaging to craniofacial surgery in 1983.[6] Prior to their work surgical procedures were planned with tracings made on paper from 2D radiographs. Frontal and lateral radiographs were taken and the silhouette lines of bony skull edges were traced onto paper. Cutouts were then made of the desired bone fragments and manipulated. The clinician would move the bone fragment cutout in the paper simulation until the overall structure approximated normal. Measurements would be taken and compared to an ideal, and another cycle of cut-and-try would be carried out. These hand-done optimization procedures would be repeated until a surgical plan was derived that promised to yield the most normal-looking face for the patient.

Between 1983-1986 March, Vannier and their colleagues computerized each step of this 2D optimization cycle.[7] The 3D visualizations overcame some of the deficiencies in the older 2D process. Two-dimensional planning, for instance, is of little use in attempting to consider the result of rotations. Cutouts planned in one view are no longer correct when rotated to another view. Volume rendering of 2D slices in the computer overcame this problem. Moreover, comparison of the 3D preoperative and postoperative visualization often suggested an improved surgical design in retrospect. A frequent problem in craniofacial surgery is the necessity of having to perform further surgeries to get the final optimal result. For instance placement of bone grafts in gaps leads to varying degrees of resorption. Similarly a section of the patient's facial bones may not grow after the operation, or attachment of soft tissues to bone fragments may constrain the fragment's movement. These and other problems suggested the value of a surgical simulator that would assemble a 3D interactive model of the patient from imaging data, provide the surgeon with tools similar to engineering computer-aided design tools for manipulating objects, and allow him to compare "before" and "after" views to generate an optimal surgical plan. In 1986 March and Vannier developed the first simulator by applying commercial CAD software to provide an automated optimization of bone fragment position to "best fit" normal form.[8] Since then customized programs designed specifically for craniofacial surgery have made it possible to construct multiple preoperative surgical plans for correcting a particular problem, allowing the surgeon to make the optimal choice.

These early models were further extended in an attempt to make them reflect not only the geometry but also the physical properties of bone and tissues, thus rendering them truly quantitative and predictive. R.M. Koch, M.H. Gross, and colleagues from the ETH Zurich, for example, applied physics-based finite element modeling to facial reconstructive surgery.[9] Going beyond a "best fit" geometrical modeling among facial bones, their approach is to construct triangular prism elements consisting of a facial layer and five layers of epidermis, dermis, sub-cutaneous connective tissue, fascia, and muscles, each connected to one another by springs of various stiffness. The stiffness parameters for the soft tissues are assigned on the basis of segmentation of CT scan data. In this model each prism-shaped volume element has its own physics. All interactive procedures such as bone and soft tissue repositioning are performed under the guidance of the modeling system, which feeds the processed geometry into the finite element model program. The resulting shape is generated from minimizing the global energy of the surface under the presence of external forces. The result is the ability to generate highly realistic 3D images of the postsurgical shape. Computationally based surgery analogous to the craniofacial surgery described above has been introduced in eye surgeries, in prostate, orthopedic, lung and liver surgeries, and in repair of cerebral aneurysms.

Equally impressive applications of computational modeling have been introduced into cardiovascular surgery. In this field simulation techniques have gone beyond modeling structure to simulating function, such as blood flow in the individual patient who needs, for example, a coronary bypass surgery. Charles A. Taylor and colleagues at the Stanford Medical Center have demonstrated a system that creates a patient-specific three-dimensional finite element model of the patient's vasculature and blood flow under a variety of conditions. A software simulation system using equations governing blood flow in arteries then provides a set of tools that allows the physician to predict the outcome of alternate treatment plans on vascular hemodynamics. With such systems predictive medicine has arrived.

Medical Avatars: Surgery as Interface Problem

Such examples demonstrate that computational modeling has added an entirely new dimension to surgery. For the first time the surgeon is able to plan and simulate a surgery based on a mathematical model that reflects the actual anatomy and physiology of the individual patient. Moreover, the model need not stay outside the operating room. Several groups of researchers have used these models to develop "augmented reality" systems that produce a precise, scaleable registration of the model on the patient so that a fusion of the model and the 3D stereo camera images is made. The structures rendered from preoperative MRI or CT data are registered on the patient's body and displayed simultaneously to the surgeon in near-to-real-time. Intense efforts are underway to develop real-time volume rendering of CT, MRI, and ultrasound data as the visual component in image-guided surgery. Intraoperative position-sensing enhances the surgeon's ability to execute a surgical plan based on 3D CT and MRI by providing a precise determination of his tools' locations in the geography of the patient.[10] This procedure has been carried out successfully in removing brain tumors and in a number of prostatectomies in the Mayo Clinic's Virtual Reality Assisted Surgery Program (VRASP) headed by Richard Robb.

In addition to improving the performance of surgeons by putting predictive modeling and mathematically precise planning at their disposal, computers are playing a major role in improving surgical outcomes by providing surgeons opportunities to train and rehearse important procedures before they go into the operating theater. By 1995 modeling and planning systems began to be implemented in both surgical training simulators and in real time surgeries. One of the first systems to incorporate all these features in a surgical simulator was developed for eye surgery by MIT robotics scientist Ian Hunter. Hunter's microsurgical robot (MSR) system incorporated features described above such as data acquisition by CT and MRI scanning, use of finite element modeling of the planned surgical procedure, a force-reflecting haptic feedback system which enables the perception of tissue cutting forces, including those that would normally be imperceptible to the surgeon if they were transmitted directly to his hands.[11]

Surgery demands an interface. The surgeon is on the outside. The targeted anatomy is on the inside. Minimally invasive laparoscopic surgery is typically performed by making a small incision in the patient's body and inserting a long shafted instrument. At the far end of the shaft is the working tip of the instrument that contacts the target anatomy inside the patient. At the near end of the shaft is the mechanism (typically finger loops) handled by the surgeon outside the patient. The mechanism outside the patient is the master component that controls the action of the slave mechanism inside the patient. The shaft provides a physical link or interface between master and slave. But laparoscopic systems have a number of problems. While minimally invasive laparoscopic surgical methods permit smaller entry incisions, the entry point fulcrum inverts hand movements, limits degrees of freedom, and amplifies tremor, making the surgery more difficult. Robotic systems combining virtual reality interfaces with haptic feedback such Hunter's prototype and a similar system developed by researchers at the University of Washington's Human Interface Technology Laboratory (HIT Lab) can overcome these problems with minimally invasive laparoscopic methods.[12] By performing the procedure with a robot, one can numerically remap the relationship between the surgeon and the instruments. The surgeon's head and hand movements are tracked by the system. The system performs inverse kinematic transformations so that the artifacts of the fulcrum point are effectively bypassed, making the surgeon's movements appear to drive the instruments as if he were literally present at the site of the surgical procedure. This provides more direct manipulations resembling those of open surgery, while maintaining the benefits of minimal incision. By controlling the articulated endoscope with the surgeon's head movements and feeding the endoscopic image back to a head-mounted display, one gives the surgeon the impression of being immersed into the patient's body. Additional scaling transformations and tremor filtering map large movements by the surgeon to smoothed accurate microsurgical movements by the robot.

Immersive robotic surgical interfaces fusing the haptic environment with 3D stereo camera images fed to a head-mounted display gives the surgeon the perspective of being placed inside the patient's body and shrunk to the scale of the target anatomy. Such systems are valuable as training devices. As if in a flight simulator the surgeon could rehearse his procedure on the model of the individual patient he had constructed. In addition, the model could be used as a training site for student surgeons, co-present during a practice surgery, sharing the same video screen and feeling the same surgical moves as the master surgeon. But such systems can also be deployed in a collaborative telesurgery system, allowing different specialists to be faded in to “take the controls” during different parts of the procedure. Indeed, a “collaborative clinic” incorporating these features was demonstrated at NASA-Ames on May 5, 1999 with participants at five different sites around the US.

[Figure # Hunter, et al. *Presence*, vol 2, showing “fade in” of student surgeons.]

Such demonstrations point to the possibility in the not distant future of new type of operating theater. In place of the all too typical scene of the crowded operating theater with assistants and technicians we could expect to see a lone surgeon seated at an operating console powered by Silicon Graphics Infinite Reality Engines potentially communicating simultaneously with participant surgeons located at distant sites, with online access to virtual reference tools, including a library of distributed virtual objects, and the databanks of the National Institute of Health's Digital Human via the Scaleable Coherent Interface on Fiber Channel at 8 gigabits per second. Although seated alone at his console the surgeon would actually be assisted by a team of surgeons and support technicians in an OR with whom he is virtually present; they see him as he performs the delicate surgery with them.

The scenario envisioned 5-10 years in the future by the National Research Council's Committee on Virtual Reality Research illustrates how future surgeons may be trained to use these surgical interfaces. In a discussion of use of VR in training heart surgeons, VR researchers describe how haptic augmentation can correct the tremors of the hand as it guides a scalpel over a beating heart:

> Jennifer Roberts ... is training to become a surgeon and is at her SE (surgical environment) station studying past heart operations. She previously spent many hours familiarizing herself with the structure and function of the heart by working with the virtual heart system she acquired after deciding to return to medical school and to specialize in heart surgery. This system includes a special virtual-heart computer program obtained from the National Medical Library of Physical/Computational Models of Human Body Systems and a special haptic interface that enables her to interact manually with the virtual heart. Special scientific visualization subroutines enable her to see, hear, and feel the heart (and its various component subsystems) from various vantage points and at various scales. Also, the haptic interface, which includes a special suite of surgical tool handles for use in surgical simulation (analogous to the force-feedback controls used in advanced simulations of flying or driving), enables her to practice various types of surgical operations on the heart. As part of this practice, she sometimes deliberately deviates from the recommended surgical procedures in order to observe the effects of such deviations. However, in order to prevent her medical school tutor (who has access to stored versions of these practice runs on his own SE station) from thinking that these deviations are unintentional (and therefore that she is poor material for surgical training), she always indicates her intention to deviate at the beginning of the surgical run.
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> Her training also includes studying heart action in real humans by using see-through displays (augmented reality) that enable the viewer to combine normal visual images of the subject with images of the beating heart derived (in real time) from ultrasound scans. Although there are still some minor imperfections in

the performance of the subsystem used to align the two types of visual images, the overall system provides the user with what many years ago (in Superman comics) was called X-ray vision. In this portion of her training, Jennifer examines the effect of position, respiration, exercise, and medication on heart action using both the see-through display and the traditional auditory display of heart sounds.

Today, Jennifer is studying recordings of a number of past real heart operations that had been recorded at the Master Surgical Center in Baltimore. In all of these operations, the surgery was performed by means of a surgical teleoperator system. Such systems not only enable remote surgery to be performed, but also increase surgical precision (e.g. elimination of hand tremor) and decrease need for immobilization of the heart during surgery (the surgical telerobot is designed to track the motion of the heart and to move the scalpel along with the heart in such a way that the relative position of the scalpel and the target can be precisely controlled even when the heart is beating).

The human operator of these surgical teleoperator systems generally has access not only to real-time visual images of the heart via the telerobotic cameras employed in the system, but also to augmented-reality information derived from other forms of sensing and overlaid on the real images. Some of these other images, like the ultrasound image mentioned above are derived in real time; others summarize information obtained at previous times and contribute to the surgeon's awareness of the patient's heart history.

All the operations performed with such telerobotic surgery systems are recorded and stored using visual, auditory, and mechanical recording and storage systems. These operations can then be replayed at any time (and the operation felt as well as seen and heard) by any individual such as Jennifer, who has the appropriate replay equipment available. Recordings are generally labeled "master," "ordinary," and "botched," according to the quality of the operation performed. As one might expect, the American Medical Association initially objected to the recording of operations; however, they agreed to it when a system was developed that guaranteed anonymity of the surgeon and the Supreme Court ruled that patients and insurance companies would not have access to the information. This particular evening, Jennifer is examining two master double-bypass operations and one botched triple-bypass operation.

During her training time on the following day, she is going to monitor a heart operation in real time being performed by a surgeon at the Master Surgical Center in Baltimore on a patient in a rural area of Maryland roughly 200 miles away. Although substantial advances have been made in combating problems of transport delay in remote surgery (by means of new supervisory control techniques), very few heart operations are being conducted remotely at ranges over 500 miles.[13]

This scenario builds its vision of the future from systems like Hunter's microsurgical robot. Among the many remarkable features in this account, perhaps one of the most salient for my purposes is the medialization and simultaneously rewriting of human agency depicted. The Committee focuses on the utility of the system for teaching purposes. In Hunter's system multiple participants can be "faded in" and "faded out" so that they actually feel what the surgeon directing the robot feels (See accompanying figure). But here a reverse video effect seems to set in: it is difficult to determine who is in control, robot system or human. A human team clearly programs the robot, but the robot enhances perception and actually guides the hand of the surgeon, correcting for errors due to (human-generated) hand tremor. The guiding hand of the microsurgical system "trains" Jennifer's erratic movements.

Surgery in an Age of Medialization

The microsurgical systems I have sketched above are by no means wild fantasies of techno-enthusiast surgeons. After little more than a decade of serious development, many of these systems are already in use in select areas in Europe and several have been approved for clinical trials in the US. To be sure, these developments are by no means a large movement in contemporary medicine; they constitute a fraction of funds spent on medical development. Nevertheless it is intriguing to ponder the conditions that would lead them to be implemented more widely and the consequences entailed for both patients and surgeons were these technologies to become widely adopted. Let’s begin by considering the arguments of proponents of the systems and the economic and political pressures that support their efforts.

Proponents of these new systems advance arguments based on claims for cost-saving measures the new technologies permit as a result of less invasive procedures and improved recovery chances of patients due to limitation of blood loss during surgeries that are more accurately planned and more precisely executed. Proponents also point to more efficient use of costly facilities through telepresence and the improvement of training regimes for surgeons. Such arguments question our tolerance for high error rates in surgeries (greater that 10% in some areas) whereas in other areas of risk, such as pilot training for commercial airlines, we would find even a 2% error rate intolerable. In the case of pilot error, one reason for the low incidence of error is arguably the availability of high-quality simulation technology for training.

A salient feature of contemporary health care is its attention to designing health care plans, diagnoses and therapies targeted for the individual patient. This coincides with the demand for greater involvement by individuals in decisions related to their own health. The new surgical techniques map onto these concerns for individually tailored therapies. As I have suggested above, the new modeling and simulation tools enable the design of procedures based on actual patient data rather than on generic experience with a condition—procedure “x” is what you do in situation “y”. Dynamic simulation and modeling tools enable surgeons to construct alternative surgical plans based on actual anatomic and physiological data projected to specific outcomes in terms of lifestyle and patient expectations. Proponents argue that the new surgical tools take the guesswork out of choosing a procedure specific to the case at hand. Such outcomes not only increase patient satisfaction but reduce costly repetition of procedures that were not optimized on the first pass.

The downside of this greater precision for the patient, of course, is increased surveillance. It is strangely ironic that while the new technology brings the capability to design therapies—including drugs—specifically targeted for the individual, and hence freeing the individual from infirmity and disease in a way never before imagined, it does so most efficiently and cost-effectively by instituting a massive system of preventive health care from genome to lifestyle. In the age of medialization your lifestyle is medicalized.

It is not difficult to see how the surgical systems explored here would mesh with such a system. The systems I have discussed deploy anatomical overlays and patient-related data as aids to the surgical procedure, but other layers of augmentation can be foreseen. Analogous to the insertion of material constraints, cost-factors, and building code regulations in current CAD-CAM design tools, surgical simulators could be augmented with the list of allowable procedures the patient's HMO authorizes, and within this list various treatment packages could be prescribed according to benefit plan. Currently in a number of states, hospitals and managed care facilities that receive reimbursement from Medicaid dollars are required to treat patients with a prioritized list of diagnoses and procedures, ranked according to criteria such as life expectancy, quality of life, cost effectiveness of a treatment and the scope of its benefits. The Oregon Health Plan, which first implemented this system, ranked 700 diagnoses and treatments in order of importance. Items below line 587 are disallowed.[14] Currently in facilities such as emergency rooms a staff supervisor examines the treatment prescribed by staff physicians, and physician-decisions to ignore the guidelines require the prescribing physician to produce a formal written justification. Physicians are reluctant to confront this additional layer of bureaucracy, particularly since the financial risks incurred by denial of Medicaid funding can be a potential source of friction with the management of the HMO employing them. In the future the appropriate constraints and efficiency measures could be pre-programmed into the surgical treatment planning simulator.

The new computer-intensive, highly networked surgical systems I have explored also carry consequences for the discipline of surgery and for the agent we call “surgeon.” In the age of heroic medicine, the days before the advent of the corporate health care system, surgeons were celebrated as among the most autonomous of professional agents. Society granted these demi-gods of the surgical wards great status and autonomy in exchange for their ability to bring massive amounts of scientific and medical knowledge to bear in a heartbeat of surgical practice.[15] These guys had the proverbial “right stuff,” agency par excellence. But in the telerobotics systems examined here, the surgeon-function dissolves into the ever more computationally mediated technologies of apperception, diagnosis, decision, gesture, and speech. The once autonomous surgeon-agent is being displaced by a collection of software agents embedded in megabits of computer code. How is this possible?

Consider the surgeon planning an arterial stent-graft before the advent of real-time volume rendering. He used a medical atlas—or perhaps more recently a 3D medical viewer—in combination with echocardiograms, CAT scans, and MRI images of his patient. At best the surgeon dealt with a stack of 2-dimensional representations, slices separated by several millimeters. These were mentally integrated in the surgeon's imagination and compared with the anatomy of the standard human. Through this complex process of internalization, reasoning and imagining, the surgeon "saw" structures he would expect to be seeing as he performed the actual surgery, a quasi-virtual surgical template in his imagination. The surgeon worked as the head of a team in the operating room with anesthesiologists, and several surgical assistants, but the surgeon mentally planned and executed the surgery him or herself. No matter how you slice it, the position of the surgeon as an autonomous center of agency and responsibility was crucial to this system.

In the new surgical paradigm the surgeon first begins with the patient dataset of MRI, CAT and other physiological data. He or she enters that data into a surgical model utilizing a variety of software and data management tools to construct a simulation of the surgery to be performed. An entire suite of software tools enables the construction of such a simulation depending on the type of procedure to be performed. The Virtual Workbench, Cyberscalpel, and various systems for interfacing anatomical and physiological data with finite element modeling tools are all elements of this new repertoire of tools for preparing a surgery. A surgical plan is constructed listing the navigational coordinates, step-by-step procedures, and specific patient data important to keep in mind at critical points. The simulation is in fact an interactive hypermedia document.

Voxel-Man provides is a particularly clear illustration of this hypertextualization of the surgical body. The key idea underlying the approach is to combine in one single framework a computer-generated spatial model to which a complete atlas with textual description of whatever detail necessary for every volume element in all the anatomical structures along the path of a surgery. These constituents differ for the different domains of knowledge such as structural and functional anatomy. The same voxel (volume pixel element) may belong to different voxel sets with respect to the particular domain. The membership is characterized by object labels which are stored in "attribute volumes" congruent to the image volume, including features like vulnerability or mechanical properties, which might be important for the surgical simulation. Also included can be patient-specific data for that particular region, such as the specific frames of MRI or CAT data used to construct the simulation.

Such intelligent volumes are not only for preparing the surgery, or later for teaching and review. Built into the patient-specific surgical plan, the hypertext atlas assumes the role of surgical companion in an "augmented reality" system. In Hunter's surgical manipulator, for example, various pieces of information—patient-specific data, such as MRI records, or particular annotations the surgical team had made in preparing the plan—appear in the margins of the visual simulation indicating particular aspects of the procedure to be performed at the given stage of the surgery. The surgeon-team and the procedures it designs are thus inscribed in a vast hypertext narrative of spatialized scripts to be activated as the procedure unfolds.

Well before we enter the operating room of the future, it is clear that the surgeons are going to be significantly reconfigured in terms of skills and background. Two processes are driving that reconfiguration: medialization and postmodern distributed production. Key to medialization is the externalization of formerly internal mental processes, the literalization of skill in an inscription device.[16] This process is abundantly evident in the introduction of new media technologies in surgery, such as computer visualization, modeling and simulation modules, and computer-generated virtual reality interfaces for interacting with the patient's body. Whereas various aspects of the visualization and pre-surgical planning took place in the surgeon's well-trained imagination, those mental skills are now being externalized into object-oriented software modules; and the surgeon's delicate manual dexterity acquired through years of training is being coded into haptic interface modules that will accompany, guide, and in many cases assist the surgeon in carrying out a difficult procedure. How will all this affect the heroic subject we've called surgeon? Will that new techno-supersurgeon be an upgrade on the last generation heroic surgeon? Such a surgeon would undoubtedly have background knowledge in the texts and practices of anatomy, biochemistry, physiology, and pathology including some traditional practices from earlier generations. But they will require familiarity if not hands-on experience in new fields such as biophysics, computer graphics and animation, biorobotics, mechanical, and biomedical engineering. They will also need to be aware of the importance of network services and bandwidth issues as enabling components of their practice. Obviously, it is unrealistic to assume that last generation's heroic surgeon is going to come repackaged with all these features, anymore than next year's undergraduates are going to show up to math class with slide rulers. If we have learned anything about postmodern distributed production, it is to expect flat organizational structures, distributed teamwork, and modularization. Thus, given the complexity of all these fields, surgical systems will likely come packaged as turnkey systems. Many surgeons will be operators of these systems, performing "routine" cardiac bypass surgeries implementing pre-designed surgical plans from a library of stored simulations owned by the company employing them. I am not saying that surgeons will simply become technicians or that surgery will cease to be a highly creative field. What I am saying, however, is that creativity will be of a different sort as many of the functions now internalized by surgeons get externalized into packaged surgical design tools, computer aided design packages such as Autocad, 3D Studio Max, or Maya have reconfigured the training, design practices, and the creativity of architects. Some surgeons with access to resources will undoubtedly engage in high-level surgical design work, but that process will be highly mediated in teamwork involving software engineers, robotics experts, and a host of others.

Other specialties connected with surgery will be similarly altered by the medialization of surgery. Consider the impact on radiology. The radiologist has been crucial to the surgeon's ability to carry off such a complex surgery prior to the age of medialization. Like the surgeon, the radiologist has been a highly valued and relatively autonomous agent. As a key professional in the surgical design process, the radiologist would make xrays and more recently CAT, MRI, or various other types of scanning modalities appropriate to the diagnosis of a suspected disease. Examining a dozen or so images, or more recently, a hundred or so slices of a CAT or MRI scan, the radiologist would prepare a diagnostic report for the surgeon. Like the similar skill of the physician, the radiologist's diagnosis was heavily dependent on acquiring keen mental skills of observation for detecting artifacts and spotting lesions or other abnormalities that would be the subject of the report. But the relative autonomy of the radiologist and his or her relationship to the diagnostic and surgical design process will certainly change in the near future. As real-time computer generated imaging becomes the norm, software tools for visualization and automated segmentation of tissues will displace the radiologist as interpreter of the data. Indeed, pressures are already mounting in this direction as the manufacturers of imaging systems such as GE, Siemens, and Brücke install systems that rapidly generate over a thousand images rather than a few dozen slices. Radiologists are currently under siege by an explosion of new data. Given the cardinal rule of data processing that valuable data should not go unused, the segmentation of this data into tissues, organs, and other anatomical structures together with the detection of abnormalities is becoming a problem for software automation. As automated tools for handling the explosion of imaging data arrive, the radiologist will undoubtedly reorient his or her professional activity and training to focus on new problems, such as construction of surgical simulations. To do so, the radiologists will work closely with computer programmers and software engineers. Needless to say, if radiology as a medical specialty survives, the background, types of knowledge, and training of its practitioners will be radically different.

Endnotes

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