The Virtual Surgeon: Operating on the Data in an Age of Medialization

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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 the 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 Baudrillard 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 on modestly preplanned scripts, adjusting them in the operating room to fit the peculiar case at hand. To perform an operation, surgeons must increasingly use extensive three-dimensional-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 widely successful endoscopic devices appeared. First among these were arthroscopes for orthopedic surgery, available in most large hospitals by 1975, but at that point endoscopy was 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 laparoscope was an initial 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 on a video monitor by all members of the surgical team rather than by just 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 industry in biomedical devices, such as new, specialized instruments for tissue handling, cutting, hemostasis, and more, sprang up almost immediately to provide the necessary ancillary technology to make laparoscopic procedures practical in your local hospital.

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 health care 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 pathbreaking 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 the Stanford Research Institute (SRI), the Johns Hopkins Institute for Information Enhanced Medicine, the 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 telerobotically perform complex surgical procedures that demand great dexterity. These workstations would re-create and magnify all of the motor, visual, and tactile sensations the surgeon would actually experience 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 operators the complex sensory feedback and motor control they would have if they were actually at the work site, carrying out the operation with their 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 a diagram showing the concept of workstation, viewing arrangement, and manipulation configuration used in the surgical telepresence systems today (fig. 1). 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, three-dimensional 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 five degrees of freedom and extremely sensitive tactile response (fig. 2).

In late 1995 SRI licensed this technology to Intuitive Surgical, Inc., of Mountain View, California. 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 the 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 three-dimensional 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 (figs. 3, 4).

A further crucial improvement to the system was brought by Kenneth Salisbury from the MIT Artificial Intelligence Laboratory. Salisbury imported ideas from the force-reflecting haptic feedback system he and Thomas Massie invented as the basis of their PHANTOM system,[2] a device invented in 1993 permitting touch interactions between a human user and a remote virtual and physical environment. The PHANTOM is a desktop device that provides a force-reflecting interface between the 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 fingertip 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

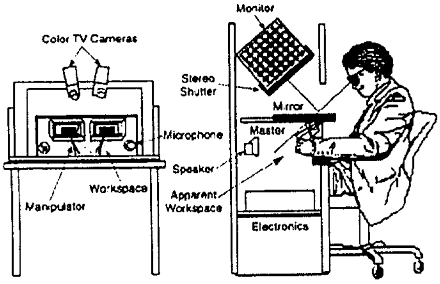

Figure 1.
Philip Green, schema for force-reflecting surgical manipulator, Stanford Research Institute, Menlo Park, CA, 1992

Figure 2.
Philip Green, force-reflecting surgical manipulator, *Time* magazine, Special Issue, Fall 1996

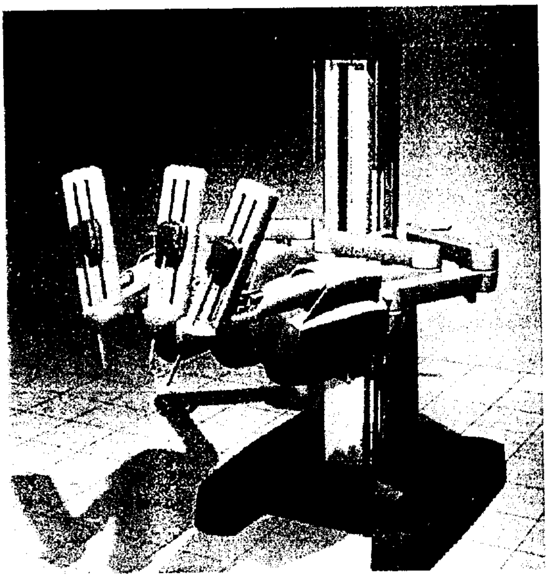

Figure 3.
Intuitive Surgical DaVinci Computer Assisted Robotic Unit, from Intuitive Surgical promotional material, Intuitive Surgical, Palo Alto, CA, 1999

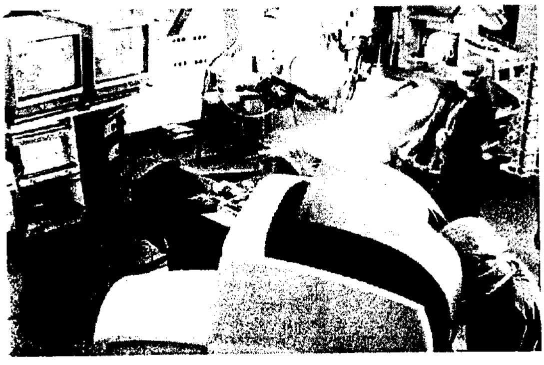

Figure 4.
Endoscopic bypass surgery, Paris, 1999, using Intuitive Surgical system, photo from Intuitive Surgical press release

object. The PHANTOM can duplicate all sorts of textures, including coarse, slippery, spongy, or even sticky surfaces. It also reproduces friction. And if two PHANTOMs 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.[3] In June of 1998, the same team performed the world's first closed-chest videoendoscopic coronary bypass surgery completely through small (1 cm) ports in the chest wall. Since that time more than 250 heart surgeries and 150 completely videoendoscopic 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 for many types of surgery. Because these modalities, particularly CT and MRI, produce two-dimensional "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 three-dimensional visualization.[4] Three-dimensional modeling first developed in craniofacial surgery because it focused on bone, and CT scanning was more highly evolved. Another reason was that in contrast to many areas of surgery where a series of two-dimensional slices—the outline of a tumor for example—provides all the information the surgeon needs, in craniofacial surgery the surgeon must focus on the skull in its entirety rather than on one small section at a time.

Jeffrey March and Michael Vannier pioneered the application of three-dimensional computer imaging to craniofacial surgery in 1983.[5] Prior to their work, surgical procedures were planned with tracings made on paper from two-dimensional 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 and 1986, March, Vannier, and their colleagues computerized each step of this two-dimensional optimization cycle.[6] The three-dimensional visualizations overcame some of the deficiencies in the older two-dimensional process. Two-dimensional planning 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 two-dimensional slices in the computer overcame this problem. Moreover, comparison of the three-dimensional preoperative and postoperative visualizations often suggested an improved surgical design in retrospect. A frequent problem in craniofacial surgery is the necessity of having to perform additional surgeries to get the optimal final 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 fragments' movement. These and other problems suggested the value of a surgical simulator that would assemble a three-dimensional 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 or her to compare "before" and "after" views to generate an optimal surgical plan. In 1986 March and Vannier developed the first simulator by using commercial CAD software to provide an automated optimization of bone fragment position to "best fit" normal form.[7] 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 (Eidgenössische Technische Hochschule) Zürich, for example, applied physics-based finite element modeling to facial reconstructive surgery.[8] Going beyond a "best fit" geometrical modeling among facial bones, their approach is to construct triangular prism elements consisting of five layers of epidermis, dermis, subcutaneous connective tissue, fascia, and muscles, each connected to one another by springs of various stiffnesses. 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 modeling program. The resulting shape is generated by minimizing the global energy of the surface under the presence of external forces. The result is the ability to generate highly realistic three-dimensional 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, 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.[9] 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 three-dimensional 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 three-dimensional CT and MRI by providing a precise determination of his tools' locations in the geography of the patient. 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 (fig. 5). Hunter's microsurgical robot (MSR)

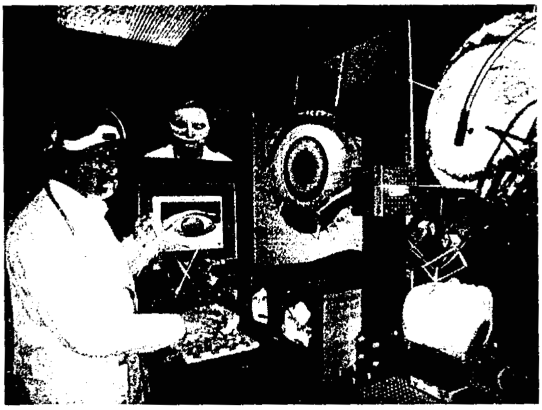

Figure 5.
Ian Hunter's microsurgical robot, *Presence: Teleoperators and Virtual Environments*, vol. 2, 1993

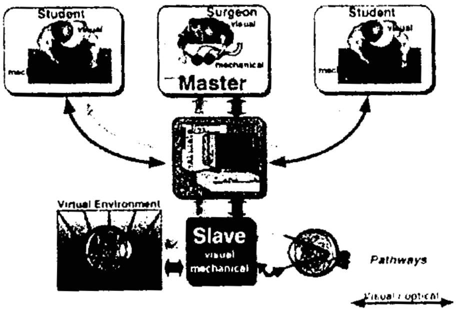

Figure 6.
Ian Hunter et al., *Presence*, vol. 2, 1993, showing "fade-in" of student surgeons

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 if they were transmitted directly to the surgeon's hands.[10]

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 as 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.[11] 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 or she 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, the system gives the surgeon the impression of being immersed into the patient's body. Additional scaling transformations and tremor-filtering convert large movements by the surgeon into smoothed, accurate, microsurgical movements by the robot.

Immersive robotic surgical interfaces fusing the haptic environment with three-dimensional stereo camera images fed to a head-mounted display give 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 can rehearse the procedure on a model of the individual patient. In addition, the model can be used as a training site for student surgeons, present during a practice surgery, sharing the same video screen and feeling the same surgical moves as the master surgeon. 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 (fig. 6). Indeed, a "collaborative clinic" incorporating these features was demonstrated at NASA-Ames on May 5, 1999, with participants at five different sites around the United States.

Such demonstrations point to the possibility in the not distant future of a new type of operating theater. In place of the 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, 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 Institutes of Health's Digital Human via the Scaleable Coherent Interface on Fiber Channel at eight gigabits per second. Although seated alone at his console, the surgeon would actually be assisted by a team of surgeons and support technicians with whom he is virtually present in an operating room; they see him as he performs the delicate surgery with them.

A scenario projected five to ten years into 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 the 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. . . . 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.
>
> 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.
>
> . . . 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.[12]

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 simultaneous rewriting of human agency depicted. The Committee on Virtual Reality Research 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. 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 United States. To be sure, these developments do not represent a large movement in contemporary medicine; they account for a fraction of the funds spent on medical development. Nevertheless, it is intriguing to ponder the conditions that would lead them to be implemented more extensively 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.

Advocates of these systems claim that cost savings will result from the new technologies. Surgeries that are more accurately planned, less invasive, and more precisely executed can reduce blood loss and improve patients' recovery rates. 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 than 10 percent in some areas) whereas in other areas of risk, such as pilot training for commercial airlines, we would find even a 2 percent 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 patients in decisions related to their own health. The new surgical techniques map onto the preference for individually tailored therapies. As I have suggested above, the new modeling and simulation tools allow procedures to be designed on the basis of 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 using 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 tailored 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 technologies explored here would mesh with such a system. They deploy anatomical overlays and patient-related data as aids to the surgical procedure, but other layers of augmentation can be foreseen. Analogous to the inclusion of material constraints, cost-factors, and building-code regulations in current CAD-CAM design tools, surgical simulators could be augmented with a list of procedures authorized by the patient's HMO, and within this list various treatment packages could be prescribed according to the benefit plan. In a number of states, hospitals and managed care facilities that receive reimbursement from Medicaid 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 seven hundred diagnoses and treatments in order of importance. Items below line 587 are disallowed.[13] Currently in facilities such as emergency rooms, a staff supervisor examines the treatment prescribed by staff physicians. The prescribing physician must produce formal written justification in support of any decision to ignore the guidelines. 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 preprogrammed 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, before the advent of the corporate health care system, surgeons were celebrated as among the most autonomous of professional agents. Society granted these demigods 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.[14] These "guys" (since surgeons were overwhelmingly males) 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. A medical atlas—or perhaps more recently a three-dimensional medical viewer—was used in combination with echocardiograms, CT scans, and MRI images of the patient. At best the surgeon dealt with a stack of two-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, surgeons "saw" structures they would expect to be seeing as they performed the actual surgery, a quasi-virtual surgical template in their imagination. The surgeon worked as the head of a team in the operating room, with anesthesiologists and several surgical assistants, but it was the surgeon as an individual who mentally planned and executed the surgery. 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, CT, 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. 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, a virtual, three-dimensional atlas of anatomy, provides a particularly clear illustration of this hypertextualization of the surgical body.[15] Its approach is to combine in a single framework a computer-generated spatial model and an atlas (containing textual descriptions) of the details of every volume element in the anatomical structures along the path of the surgery. These constituents vary with 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 that 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 CT 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 a 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 surgeons will 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 presurgical planning took place in the surgeon's well-trained imagination, those mental skills are now being externalized into object-oriented software modules. 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's heroic surgeon? The new surgeons 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 with, if not hands-on experience in, new fields such as biophysics, computer graphics and animation, biorobotics, and 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. It is obviously unrealistic to assume that last generation's heroic surgeon will come repackaged with all these features, any more than next year's undergraduates will come to math class with slide rules. 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 that implement predesigned surgical plans from a library of stored simulations owned by the company employing them. I don't mean that surgeons will simply become technicians or that surgery will cease to be a highly creative field. However, that creativity will be of a different sort, as many of the functions now internalized by surgeons are externalized into packaged surgical design tools just as computer-aided design packages such as Autocad, 3D Studio Max, or Maya have reconfigured the training, design practices, and creativity of architects. Some surgeons with access to resources will undoubtedly engage in high-level surgical design work, but that process will be mediated in teamwork involving software engineers, robotics experts, and a host of others.

Other specialties 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 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 x-rays and more recently administer CT, MRI, and various other types of scanning modalities appropriate to the diagnosis of a suspected disease. Examining a dozen or so images, or a hundred or so slices of a CT 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 the keen observational skills required 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 the 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.

Should we deplore these developments? Many feel that the increase in technical mediation of surgery that I have discussed here, together with its attendant changes in organization, financing, careers, and personnel, are steps in the direction of the dehumanization of medicine by the advance of technology. To many, just describing these systems is in some sense to celebrate them, whereas our role as medical humanists should be to critique and wherever possible resist the technical interface driving a deeper wedge between caring doctors and their patients. While sympathetic to these views, I wonder where we might locate the moral high ground in order to fashion such a critical framework. The problem, as I see it, is that there is no "there" there to critique. The episodes I have treated illustrate that while the rapidity with which these changes are taking place may suggest creeping technological determinism, this is anything but the case. Each of the technical steps I have described involves negotiations among a large network of actors, machines, and markets. The technology involved draws upon military-sponsored research in simulation, networking, and robotics. At the same time, it depends on imaging technologies driven by price reductions that derive from the entertainment industry, particularly improvements in three-dimensional computer graphics by leading-edge companies, such as Nvidia, who supply the video game industry.

The component technologies driving this surgical revolution are rapidly becoming ubiquitous. They are embedded in so many facets of our lives, from the tools of our workplaces, to our cell phones and personal digital assistants, to our means of entertainment, that it is impossible to identify the "good guys" and "bad guys." No less problematic are the values motivating the changes. Who can find fault with the professed goal of expanding the range of operable conditions, reducing blood loss and the danger of infection, and improving recovery times through advanced endoscopic procedures? Or, given the enormous costs of health care, who has a problem with the goal of making medical care efficient through training and simulation exercises linked to diagnostic and surgical procedures profiled to meet the needs of the specific individual? Haven't these goals always been the proper motivations of caring, humane medicine?

Perhaps more problematic for identifying a critical high ground is the phenomenon I have called "medialization." By this term I have sought to call attention to the ways in which the medical body is being redefined as the digital body. From stem cells to fully developed organisms, digital media provide the interface for medical intervention. But media are not transparent devices—and new media, with their increased involvement of all the senses, perhaps less so than previous media configurations. Media not only participate in creating objects of desire, they are desiring machines that shape us. Through medialization we come to desire the digital medical body. Media inscribe our situation: it is difficult to see how we can teleport ourselves to some morally neutral ground.

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2 For background on the PHANTOM system see the information at *http://www.sensable.com.*

3 For technical reports and news updates on the stages in development and approval of the Intuitive system see the archive section of the Intuitive Surgical, Inc., website: *http://www.intuitivesurgical.com.*

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9 C. A. Taylor et al., "Predictive Medicine: Computational Techniques in Therapeutic Decision-Making," *Computer Aided Surgery* 4.5 (1999): 231–47.

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12 Nathaniel I. Durlach and Anne S. Mavor, eds., *Virtual Reality: Scientific and Technological Challenges* (Washington, D.C.: National Academy Press, 1995), pp. 25–26.

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14 The classic sources on this point are Eliot Freidson, *The Profession of Medicine* (New York: Dodd, Mead, 1970); Magali Sarfatti Larson, *The Rise of Professionalism* (Berkeley: University of California Press, 1977); Charles Rosenberg, *The Care of Strangers* (New York: Basic Books, 1987); Paul Starr, *The Social Transformation of American Medicine: The Rise of a Sovereign Profession and the Making of a Vast Industry* (New York: Basic Books, 1982).

15 K. H. Höhne et al., *Voxel-Man 3D-Navigator: Inner Organs, Regional, Systemic, and Radiological Anatomy*, CD-ROM set (Berlin and Heidelberg: SpringerVerlag, 2000).

16 André Leroi-Gourhan and others have pointed out that a key feature in the construction of new media is the externalization of mental processes in an inscription device or system of inscription. See André Leroi-Gourhan, *Le geste et la parole. Dessins de l'auteur* (Paris: A. Michel, 1964). The relation of phonetic script to speech is the classical example of this phenomenon, but as Friedrich Kittler and others have pointed out, the process is evident in other inscription technologies. See Friedrich Kittler, *Discourse Networks 1800/1900* (Stanford, CA.: Stanford University Press, 1988) and Jacques Derrida, *Of Grammatology*, trans. Gayatri Spivak (Baltimore: Johns Hopkins University Press, 1976). For an excellent overview of the problem see David E. Wellbery's foreword to *Discourse Networks 1800/1900* (Stanford, CA: Stanford University Press, 1988).

By reanimating this reference we place current VR research as one more step in a long history that looks at mediated experience as the simulacrum, or the copy of the copy. And much in the same way that Plato did in the *Phaedrus*, we often frame this question in terms of the gains and losses of mediated versus bodily experience.

There is another tradition in the West that sees mediation itself as a new form of life. These ideas are cast in alchemical archetypes from Prometheus to Pygmalion, from *Frankenstein* to Genesis. This is a tradition that has explored the differences between representations and life and asks, what happens when life leaps from the page *ex vivo*? What happens when the pages of the book become the membranes for new forms of life?

Ex Vivo to *In Vivo*

Machines known as "replicators" can now generate solid physical objects from a computer-based three-dimensional numerical data representation. After processing the three-dimensional representation into stacks of two-dimensional contour maps, the machine renders the two-dimensional slices as layers of plastic. As the technology undergoes the evolutionary advances of the product cycle, solid three-dimensional objects will be manifested as readily as copies from today's laser printers.[1] Kuh-ching . . . kuh-ching . . . kuh-ching. . . . Artificial organs will be commodified if not grown.

Although related, this is very different from the dynamics of virtual experience outlined above. The three-dimensional numerical representation is not the endpoint of this production line but a soft blueprint of the final hardcopy. The map has now become the place. When this process is oriented toward the biological domain, the boundaries between natural and artificial flesh melt.

The Virtual Nature of All Objects

The blurring of the boundary between physical and virtual flesh reminds us of the virtual nature of actual physical objects. A mountain from our usual daily perspective is solid, solid, solid. But from the subatomic perspective it is mostly empty space. Visualization technologies allow us new conceptions of everyday objects. Which one is it, really? Is it solid or empty? To my mind it is both, or more precisely, solidness or emptiness is a quality of perspective rather than an inherent quality of the mountain. If we are conscious of what tools we are using to visualize objects, we can change our perspective when needed. We can thus learn that "everyday experience" is already virtual.

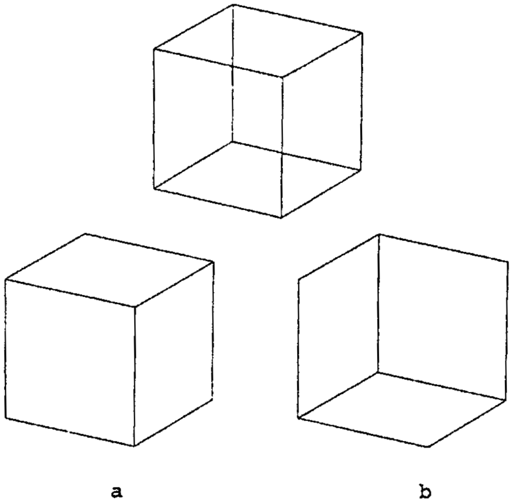

Figure 1.
Necker cube

A well-known demonstration of this is the Necker cube (fig. 1). A Necker cube has two possible three-dimensional interpretations but is just a set of lines drawn on a two-dimensional page. Which is it: three-dimensional interpretation a? Three-dimensional interpretation b? Or the lines on a two-dimensional page? The body is no different: it has a physical and a virtual interpretation. Although the brain does not so readily toggle between these interpretations as in the case of the Necker cube, the dualistic quality of our bodies remains.

Perhaps the best medical analogue to the "mostly empty space" interpretation of matter is the view of our bodies as a set of two-dimensional images stacked along an orthogonal axis. This technical, theoretically "objective" Cartesian representation is invasive to the coordinate systems of the functional structure of the body's organs. And yet this self-portrait of human anatomy is a beautiful neo-mythical expression of our nature, akin to the nuclear physicist's snapshots of scattering subatomic particles. We can see the space within the slices, but the detail of the slices may seduce us into losing track of what the slices constitute when put together. The inverse is also true; the beauty of the human form in total may seduce us, but we may thus lose track of the beauty of the spaces within the body.

In fact, the massive literature on metaphysical dualities (mind/body or otherwise) is also perhaps best viewed through the bifurcated lens of real virtual experience. In one sense, it forms a solid philosophical platform, but upon closer examination can also ultimately be perceived as the shaky ground of almost empty space.

In Vivo Ex Silica—New Virtual Space

What computer professional has not awakened in the morning to see the waking world boot up window by window? That structural representation of information confounds with a prior paradigm of things as solid objects for but a few dreamlike moments before solidifying into the Monday morning cup of coffee.

In much the same way, the virtual futures of medicine described by Lenoir will also solidify into new forms of space supporting existence for new forms of material entities. Can we orchestrate such blended paradigms to some advantage?

Virtual surgery will require new medical professionals possessing new skills. The radiologist, for instance, will be interpreting new kinds of imagery and will need a keener understanding of virtual reality technologies in order to discriminate whether an image feature of the now three-dimensional reconstruction is anatomically based or an artifact of the process.

Many of these skills will initially have to come from nontraditional settings. Can we successfully navigate these demands? Can we create fluid cultural environments that allow doctors to shift easily from viewing bodies as deconstructed slices to understanding the dynamics of how these slices fit together? Can a virtuoso video game player, pre-filtered for compassion and a sense of meticulous and fastidious thoroughness, be integrated into the surgical hyperteam whose players penetrate into the multidisciplinary and trans-hyper-phylum of posthuman cyborg? The medialization of medicine opens the possibility of such cross-referencing and repurposing of skill sets.

Transcending the Body's Duality

New materials will arise that will blend traditional metaphysical distinctions. New forms of semiotic flesh will be constituted through new forms of medical and material practice. If this can be done, then eventually the interpretation of body as mind can be reflected (à la Necker) into mind as body. "And in ultimate enlightenment, that duality fuses, vanishes, is transcended in Divine Ignorance."[2]

If one could not only embrace the dual nature of our bodies but also acknowledge the possibility of yet other unknown, if not unknowable, realities of our selves, then such a one may be an ultimate super doctor, founded in compassion and in an understanding of our multifaceted and ever mysterious nature.

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[1] Martin J. Moylan, "A Sci-fi Dream Gets Real," *Seattle Times*, July 26, 2001, p. C1.

[2] Da Avabhasa, *The Heart's Shout* (Clearlake, CA: Dawn Horse Press, 1993), p. 158.