CHAPTER THIRTEEN

# Authorship and Surgery: The Shifting Ontology of the Virtual Surgeon

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The advent of computer-mediated writing has spawned a nostalgic industry on the culture of the book and lamentations about the demise of the institutions of print culture.[1] But the changes occurring in the institutions of writing and authorship may represent even more profound shifts. As computer-mediated communication permeates our daily lives in our banks, our stores, our classrooms, and even our bedrooms, the specter of loss of human agency and autonomy—perhaps even a reconfiguration of "the human" itself—invariably surfaces. Computer scientists Hans Moravec, Ray Kurzweil, and Bill Joy are among the most recent to trumpet the emerging potential for new artificial intelligence and networking technologies to blur the boundaries between human and machine on the frontier where the soul and silicon chips unite.[2] But even before computer-mediated communication became a common experience, indeed even before the advent of personal computers, André Leroi-Gourhan speculated in his *Le Geste et la parole: Dessins de l'auteur* (1964) that by externalizing thought in matter, most palpably in the form of electronic media, writing itself—perhaps the tool that set mankind on its peculiar evolutionary trajectory—harbors the end of the human: not an apocalyptic end but the extinction of one species and its replacement by something else. It seems paradoxical that augmenting and accelerating the very tools—writing technologies—that have distinguished humanity could somehow induce a mutation and break with our past. According to Friedrich Kittler's analysis of the effect of computer-mediated writing on literature, that mutational event may be further along than we realize. Arguing that in computer-mediated writing man-made writing passes through microscopically written inscriptions, which, in contrast to all previous writing tools, are able to read and write by themselves, Kittler has suggested that the last historical act of writing may well have been the moment when, in the early 1970s, Intel engineers laid out a dozen square meters of blueprint paper in order to design the hardware architecture of their first integrated microprocessor.[3]

Changes are indeed taking place in our modes of writing and reading, but it would be premature to proclaim the death of writing. Rather, in this paper we explore the opposite claim: At no time has writing been more central to our material existence. Media inscribe our situation. We are immersed in new inscription technologies for writing and for rewriting the body, a growing repertoire of computer-based media for creating, distributing, and interacting with digitized versions of the world. In our daily activities, we witness a fusion of digital and physical reality. This fusion is not, as Baudrillard predicted, the replacement of the real by the hyperreal—the obliteration of a referent and its replacement by a model without origin or reality—but a new configuration of ubiquitous computing in which wearable computers, independent computational agent-artifacts, and material objects are all part of the landscape. To paraphrase Case in Gibson's *Neuromancer*, "data is being made flesh."[4] These new media reshape the channels of our experience, transforming our conception of the "real" and redefining what it means to perform an experiment, to formulate a "theory," to be an "author," and, some would maintain, to be a "self."[5]

Recent developments in surgery provide a site to explore these themes. Ordinarily we do not think of surgeons as authors and writers. Alongside fighter pilots and extreme athletes they are typically depicted as persons of action, autonomous agents in the most vital sense who bring vast fields of knowledge, decision-making ability, and practical technical skill to bear in a life-and-death instant. But surgery provides a dramatic example of a field newly saturated with writing technologies that are transforming the categories of subjectivity, agency, and reality. Examining computer-mediated surgery through the lens of authorship may provide a useful allegory for other domains where new computer-mediated technologies of writing are reshaping agency and subjectivity. For just as the "author" considered as a singular nodal point of intention guaranteeing the unity of a literary work is being disbursed into distributed networks, so, too, are individual surgeons being replaced by software-mediated, machine-human collectivities. And just as the experience of the text is being displaced from the fictive world generated in the reader's imagination to an interactive performance externalized in a virtual world (or headset), so, too, is the surgical intervention planned in advance in the imagination of the surgeon. Once the creative act of practical genius, surgical plans are being displaced by the construction of a multidimensional simulation that includes not only the surgeon as one of its feedback loops, but also a host of other agents, among them codes that indicate allowable procedures in the pricing structure of the patient's health maintenance organization. In the near future, surgeons will no longer boldly enact modestly preplanned scripts, modifying those scripts in actual practice to adjust for the vicissitudes of the real case (such as anatomical structures displaced from their canonical appearance in a medical atlas or pathological phenomena peculiar to the individual patient). Increasingly, surgeons must use extensive three-dimensional authoring tools to generate a simulation that becomes a software surgical interface. This interface guides the surgeon—now a collective—in performing the procedure. As we explain in more detail later, *authorship* and *surgery* are becoming indistinguishably fused, but in the process the "surgeon-author" as independent agent is disappearing.

As an example of the transformation of surgery through new writing technologies, consider Dr. Ian Hunter's performance of a surgical procedure on the eye (figure 13.1).[6] He does so in the newly emerging discourse network powered by Silicon Graphics Reality Engines, which simultaneously communicates, via the Scaleable Coherent Interface on Fiber Channel at 8 gigabits per second, with potentially hundreds of other agents and with virtual reference tools, including a library of distributed virtual objects and the databanks of the National Institute of Health's Digital Human. Although he appears singly here rather than in the more typical scene of a crowded operating theater with assistants and technicians, Dr. Hunter is assisted by a team of surgeons in an operating room with which he is virtually present. They see him as he performs the delicate surgery with them. Dr. Hunter's participation in the surgical intervention is obviously mediated by a vast technological infrastructure, and that network includes not only texts and practices of anatomy, physiology, and pathology including some traditional practices from earlier generations, but new fields such as biophysics, computer graphics and animation, biorobotics, mechanical engineering, and biomedical engineering. In contrast to a printed article in the *Journal of the American Medical Association* that previously would have crowned a successful medical achievement, Dr. Ian Hunter's work exists in a vastly co-authored interactive 3D VRML simulation of the surgical intervention that will have few paper traces. In fact, its paper traces are only intended for people such as grant officers, congressional aides, unregenerate text-bound physicians who don't currently have the technical capacity to "read" the simulation. (Lawyers, especially, will scour the printout of the code for purposes of defense litigation.) And though the institutional affiliations on the "publication" may include familiar addresses such as "Department of Surgery," there are others in this new discourse network—places such as the JHU-ISS Center for Information-Enhanced Medicine, the Mayo Clinic Biomedical Imaging Resource, Industrial Light and Magic, and IP (Internet protocol) addresses—that name completely new "sites" at machines physically located in such diverse places as the MIT Media Lab and the NASA-Ames Research Center.

Our analysis hinges on the relationships between networks and subjects. The "conditions of possibility" outlined by Michel Foucault in his discus-

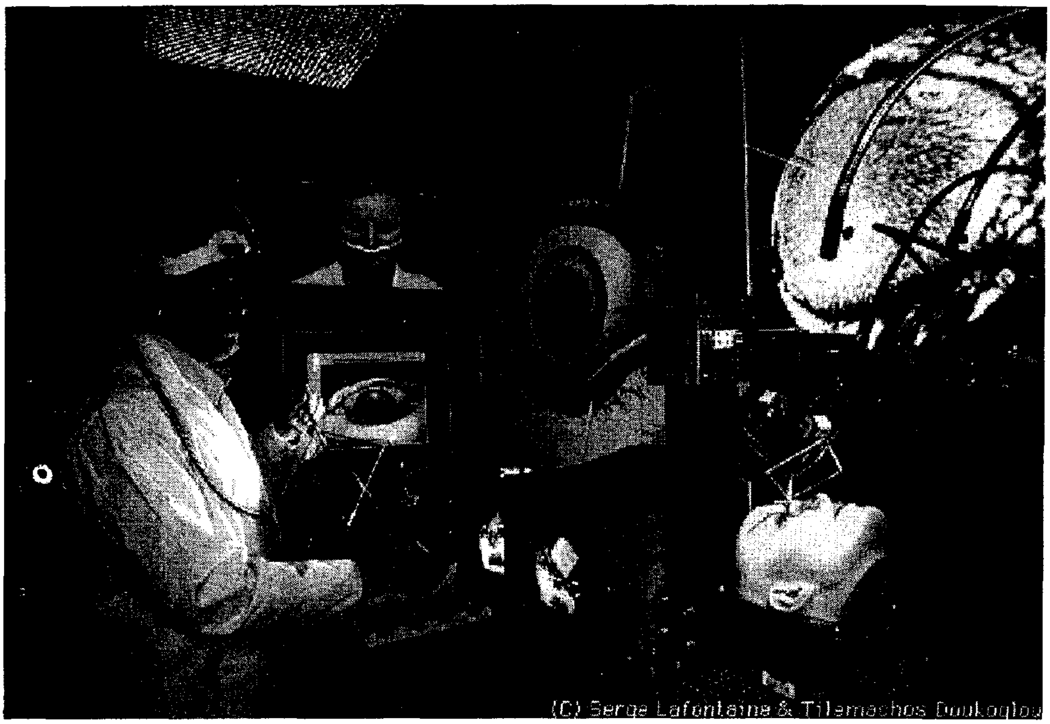



FIGURE 13.1. Ian Hunter's microsurgical robot. Source: I. W. Hunter, T. D. Doukoglou, et al., "A Teleoperated Microsurgical Robot and Associated Virtual Environment for Eye Surgery," *Presence: Teleoperators and Virtual Environments* 2:4 (1994), cover image.

sions of discourse networks and authorship provide our entry-point. As Foucault noted, the author-function is characteristic of the mode of existence, circulation, and functioning of certain discourses within a society.[7] As a result, certain types of discourses are endowed with an author-function, and others are not. Not every discourse, whether written or spoken, may be accorded the status of being the product of an author. *Author* is a position that defines a subject in a discourse network rather than a quality inherent in an individual named, for instance, "Shakespeare." The same is true of *surgeon.*

As Foucault argued in *Birth of the Clinic*,[8] *surgeon* is a position within a discursive formation, constituted by the configuration of various statement types. Moreover, this configuration of statements is inseparable from the coordination of behaviors and the organization of the senses, the literal disciplining of bodies into the agents we call *surgeon.* As every surgeon discovers in medical school, learning how to talk the talk is inseparable from learning how to walk the walk. In this sense agency is a product of the disciplining regime of discursive formations.

Our analysis draws upon two distinct features of the author-function: namely, authorship as a set of social institutions and conventions, and authorship as embedded within a specific material media-technological formation. For various reasons, the combined effect of these features in the periods Foucault studied was to locate the author in the agency of a single person. Foucault's analysis focused on the institutional aspects of authorship. He observed that texts, books, and discourses began to have authors to the extent that authors became subject to punishment. Discourse can be subversive, and in order to control the potentially transgressive acts of discourse, texts were attributed to individuals as responsible agents. Further, Foucault pointed to the appropriability of discourses, the establishment of the system of literary ownership of texts with rules concerning author's rights, rights of reproduction, and so forth.

In *The Archaeology of Knowledge*, Foucault wrote that the material existence of the signs composing a statement is crucial to its intelligibility: "The coordinates and the material status of the statement are part of its intrinsic characteristics. That is an obvious fact."[9] Certainly Foucault did not overlook the issue of materiality. But as an archaeologist he was drawn to archives holding texts inscribed exclusively on paper or on canvas with ink or paint, and even within this domain he did not consider whether the medium of typed inscription versus that of, for example, handwriting played a role in constituting the author-function. Furthermore, even admitting Foucault's paper-fetishism, he tended to dismiss the materiality of communication as insignificant in comparison with considerations of the institutions of the letter.[10]

Foucault's focus was on the conditions that determine the status of a statement, and he located status determination in social institutions: "The statement cannot be identified with a fragment of matter; but its identity varies with a complex set of material institutions. . . . The rule of materiality that statements necessarily obey is therefore of the order of the institution rather than of the spatiotemporal localization; it defines possibilities of reinscription and transcription (but also thresholds and limits), rather than limited and perishable individualities."[11] From this perspective, media may be important but only insofar as they are components of institutional structures, or are perhaps themselves considered from a certain perspective as institutions.

To go beyond Foucault's analysis it is useful to consider Marshall McLuhan's media thesis: The medium is the message. Instead of focusing on the content of media—the ideas, images, or sounds they convey—or on the institutional framework of media, McLuhan enjoins us to consider the transformative power of the media themselves. The medium is the message, McLuhan writes, "because it is the medium that shapes and controls the scale and form of human association and action."[12] Media are what configure our relations with one another and with ourselves. In McLuhan's view, media are extensions of the senses, and by amplifying any single medium, the ratio among the senses is changed. As extensions of the senses, media, according to the thesis of the materialities of communication, configure our social awareness, our experience of the world, and even our experience of ourselves.[13]

Felix Guattari has given a useful formulation of the conditions of subject formation that is sensitive to a Foucaultian consideration of discursive structures and institutions as well as to the materiality of technological media emphasized by authors such as McLuhan, Derrida, Chartier, and Kittler.[14] Of particular importance for our thesis is what Guattari calls the machinic dimensions of subjectivation.[15] Consistent with Guattari's formulation, we might regard media technology, the machines of sign production and distribution, the material substrate of the semiotic productions of the mass media, informatics, telematics, and robotics, as inseparable from the formation of subjectivity, and not just with respect to memory and information-processing, but with respect to sensibility (in much the same way McLuhan suggested).

Guattari distinguishes among three components leading to subjectivity, which we find useful for examining the ways in which computer-mediated communication potentially alters the subject, our sense of the world, and agency:

> Recognition of these machinic dimensions of subjectivation leads us to insist, in our attempt at redefinition, on the heterogeneity of the components leading to the production of subjectivity. Thus one finds in it: (1) signifying semiological components, which appear in the family, education, the environment, religion, art, sport . . . , (2) elements constructed by the media industry, the cinema, etc., [and] (3) a-signifying semiological dimensions that trigger informational sign machines, and that function in parallel or independently of the fact that they produce and convey significations and denotations, and thus escape from strictly linguistic axiomatics.[16]

This definition implies a heterogeneous set of components that mutually constitute subjectivity. Linguistic, behavioral, and institutional considerations making up what Foucault would have considered discursive formations are part of this picture. But by attributing equal importance to the "a-signifying semiological dimensions of informational sign machines," Guattari emphasizes the constitutive power of media and information technology. Reminiscent of an approach suggested by Madeleine Akrich and Bruno Latour,[17] Guattari's suggestion incorporates certain nonhuman actors, namely the machines of sign production and symbol manipulation on all levels—visual, auditory, and tactile—and the material characteristics of communication channels through which they are mobilized. If, as we believe, the position of the subject is not given by a biological or psychological a priori, but constituted through Foucaultian discursive formations and the material configuration of the senses through technological media, then the technologies of virtual reality at work in contemporary medicine are not only transforming the practices but the very "subject" of the surgeon.

The contribution of the material configuration of media in constituting the author-function is particularly salient for our case, the virtual surgeon. For more than anything else, through the absorption of computer-mediated writing technologies affecting many other disciplines, the reconfiguration of this material-media component of surgery is shifting—and along with it the subject, surgeon. Indeed, it is hard to judge whether the traditional term *surgeon* is appropriate any longer. The "surgeon" Dr. Hunter is constituted by a web of data streams coursing through high speed routers governing the flow of data packets, a vast array of massive parallel processors, complex systems of stacked algorithms, the material institutions and standards sustaining them, and not least, the graphical user interface that is Dr. Hunter's portal to this world.

In what follows, we explore conditions bringing about such a shift from the unified heroic surgeon/agent, the stereotypical embodiment of scientific expertise, technical skill, and nerves of steel, to the dispersed, robotically enhanced image of Hunter. We are registering this shift not only in the subject-position *surgeon* but also in objective surgical bodies themselves. We move from the massively resistant material body, the object of surgery on the table of our hero-surgeon, to the simulated, virtually present body of Dr. Hunter's telesurgical robotic system, a large multimodal data set solidified through floating point calculations. Concomitant with the shift in the ontology of surgical domain, we also note crucial changes in the surgeon's subjective bodily experience through the application of virtual reality to surgical intervention.

## THE MINIMALLY INVASIVE SURGERY REVOLUTION

The practical developments in surgery that interest us 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 microsurgical approaches into common operative procedures? The introduction of the small, medical video camera that is attachable to the eyepiece of the arthroscope or laparoscope. French surgeons were the first to develop small, sterilizable high-resolution video cameras that allowed all members of the team to view the surgical field by looking at a video scene together, rather than forcing the surgeon to peer down the scope alone.[18] With the further addition of halogen high-intensity light sources with fiber-optic connections, surgeons were able to obtain bright, magnified images viewable by all members of the surgical team on a video monitor, allowing cooperative teamwork and opening possibilities for surgical procedures of increasing complexity, including suturing and surgical reconstruction done only with videoendoscopic vision. The first laparoscopic cholecystectomy was performed by French surgeons in 1989.

Surgeons in France and the United States built upon this technology by developing new, specialized instruments for tissue handling, cutting, and hemostasis. Due to the benefits of small scars, less pain, and 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. Patient demand 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 rapidly rising 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 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 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 allowing 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 actually inside the patient. The aim of the programs sponsored by these agencies was 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, which allows a virtually present 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. With funding from the NIH, Green went on to design and build a demonstration system. The proposal contained the diagram shown in figure 13.2, which illustrates 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, 3-D 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.

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. Intuitive added the EndoWrist™, patented by company cofounder Frederic Moll, which contributed two additional 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). These enhancements allowed the system to better mimic a surgeon's actions, enabling the robot to reach around, beyond, and behind delicate body structures. Through licenses of IBM patents, Intuitive also improved the 3-D video imaging, navigation, and registration of the video image to the spatial frame in which the robot operates.

A further crucial improvement to the system was brought from the MIT Artificial Intelligence Laboratory by Kenneth Salisbury, who imported ideas

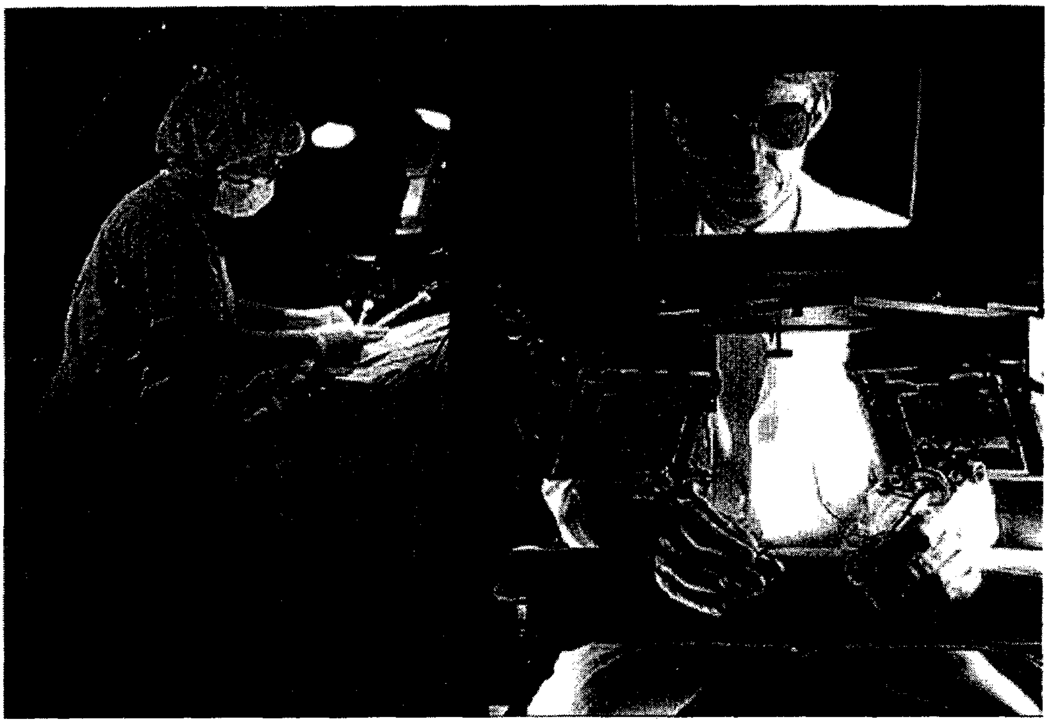


FIGURE 13.2. Philip Green, Stanford Research Institute, surgical manipulators with computer generated force feedback. Source: Philip Green, "Microsurgical Manipulators with Computer Generated Force Feedback." Source: *Time*, 148:14 (Fall 1996), 13.

from the force-reflecting haptic feedback system he and Thomas Massie invented as the basis of their PHANToM™ system, a device permitting touch interactions between human users and remote virtual and physical environments. The PHANToM™ is a desktop device that 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 fingertip and can actively exert an external force on the finger, creating compelling illusions of interaction with solid physical objects. With a stylus substituted for the thimble, users can feel the stylus tip 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 1998. From May through December of that year Professor Alain Carpentier and Dr. Didier Loulmet of the Broussais Hospital in Paris performed six open-heart surgeries using the Intuitive™ system. In June 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, which was approved for sale throughout the European Community in January 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 computerized tomography (CT), which is especially useful for bone; magnetic resonance imaging (MRI), which is useful for soft tissue, ultrasound, and later positron-emission tomography (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 two-dimensional "slices" through the patient, the natural next step (taken by Gabor Herman and his associates in 1977)[19] was to stack these slices in a computer program to produce a three-dimensional visualization. Three-dimensional modeling first developed in craniofacial surgery, a field focused on bone, whose digital imaging method of choice, CT scanning, was highly evolved. Another reason for this development was that in contrast to many areas of surgery where a series of two-dimensional slices—the outline of a tumor for example—give the surgeon all the needed information, a craniofacial surgeon must focus on the skull in its three-dimensional entirety.

Jeffrey Marsh and Michael Vannier at Washington University in St. Louis pioneered the application of three-dimensional computer imaging to craniofacial surgery in 1983.[20] 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 the clinician moved these cutouts in the paper simulation until the overall structure approximated normal. Measurements were taken and compared to an ideal, and another cycle of cut-and-try was carried out. These hand-done optimization procedures were repeated to produce a surgical plan that promised to yield the most normal-looking face for the patient.

Between 1983 and 1986 Marsh, Vannier, and their colleagues computerized each step of this two-dimensional optimization cycle.[21] The three-dimensional visualizations overcame some of the deficiencies in the older two-dimensional 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 two-dimensional slices in the computer overcame this problem. Moreover, comparison of the three-dimensional 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 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 to compare "before" and "after" views to generate an optimal surgical plan. In 1986, Marsh and Vannier developed the first simulator by applying commercial computer-aided design (CAD) software to provide an automated optimization of bone fragment position to "best fit" normal form.[22] 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 have been 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, have applied physics-based finite element modeling to facial reconstructive surgery (figure 13.3).[23] 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, subcutaneous

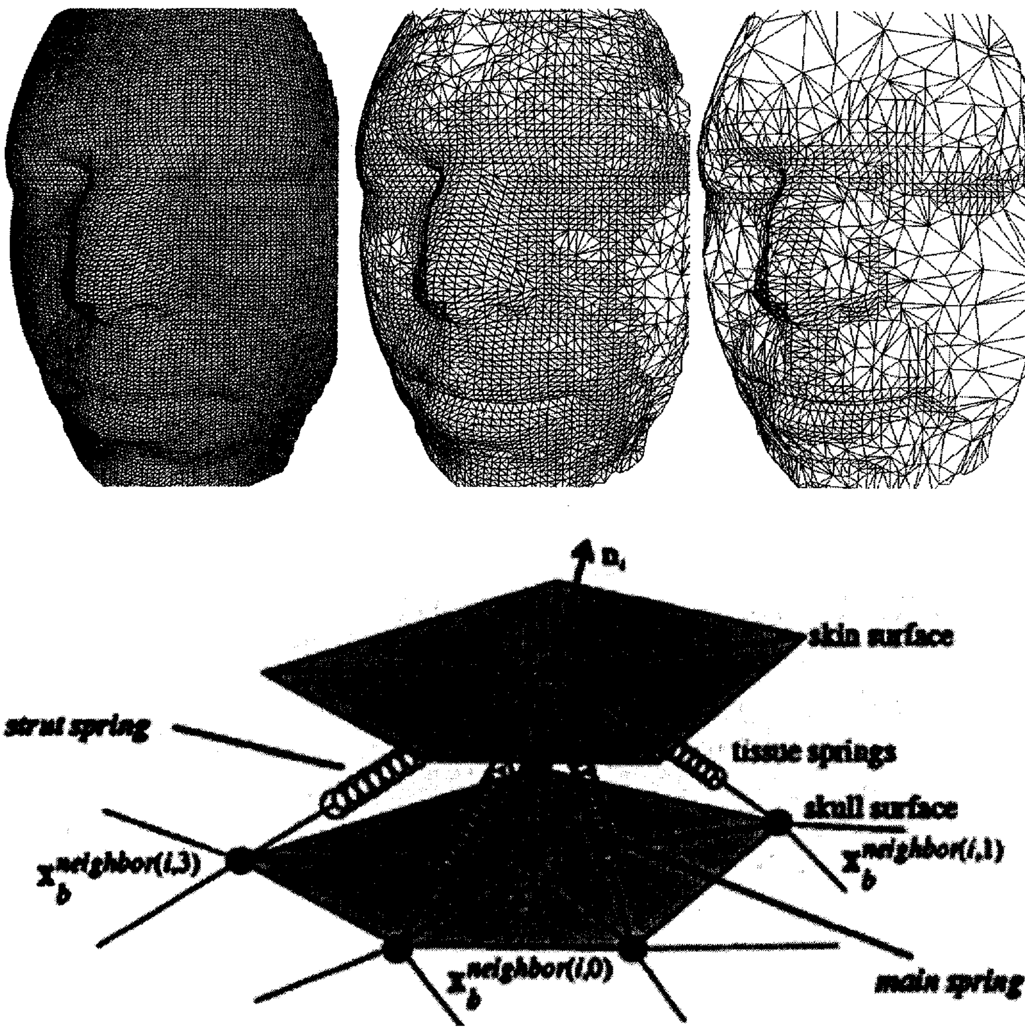



FIGURE 13.3. Craniofacial modeling with predictive tissue physics. Source: R. M. Koch, M. H. Gross, et al., "Simulating Facial Surgery Using Finite Element Models," *Siggraph 96* (1996), p. 423.

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-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 three-dimensional images of the post-surgical shape. Computationally based surgery analogous to the craniofacial surgery previously described has been introduced in eye surgeries (discussed later), in prostate, orthopedic, lung and liver surgeries, and in repair of cerebral aneurysms.

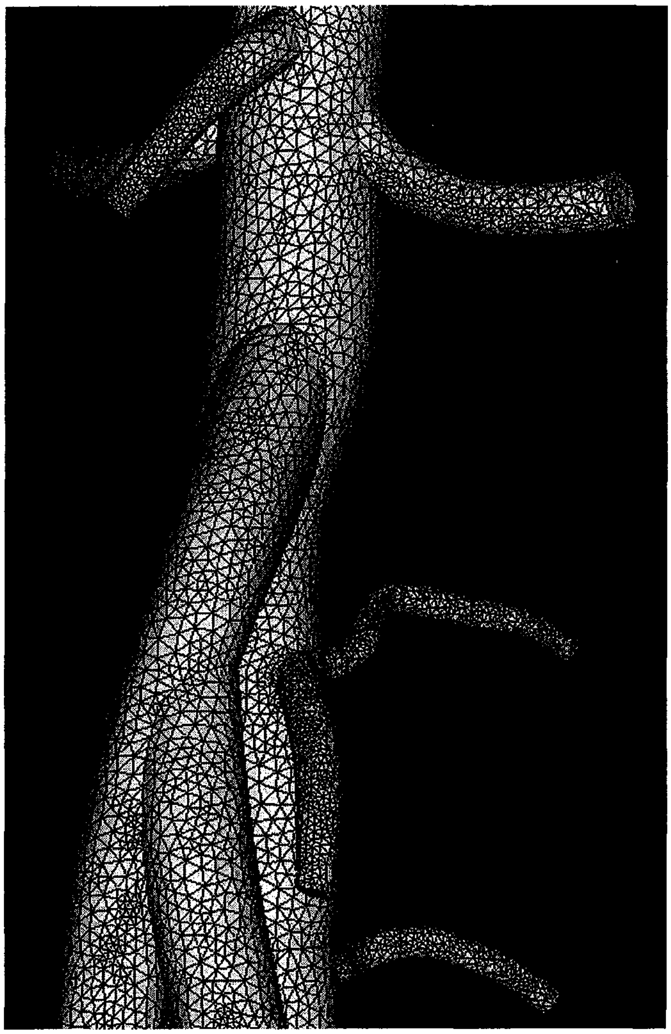


FIGURE 13.4. Charles A. Taylor, Stanford University, cardiovascular finite element modeling combining physiologic function and medical imaging data. Source: Charles A. Taylor, M. T. Draney, et al., "Predictive Medicine: Computational Techniques in Therapeutic Decision-Making," *Computer Aided Surgery* 4:5 (1999), 235.

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 3-D finite element model of the patient's vasculature and blood flow under a variety of conditions (fig. 13.4). 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. Modern medicine has prided itself on being science-based and grounded in experiment. But despite its many impressive successes, science-based medicine has never been *predictive*. The builders and advocates of these systems argue that they have crossed the Rubicon to predictive medicine.

## MEDICAL AVATARS

Computational modeling has added an entirely new dimension to surgery. In finite element modeling the patient data derived from CT, MRI scans, and other physical measurements are the inputs for the model and visualization. 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. The visualization of the patient data is then used to generate a surgical plan. The plan is the script the surgical team will perform including the path to be followed through the patient's body; the operations along the path to be performed on various structures, such as making incisions, clamping off arteries, and moving or manipulating around structures; and the repair or removal of the diseased tissues. Once the plan is constructed, a simulation of the surgery is created using the patient's data set. The surgical simulator is a VR system that combines the three-dimensional images of the patient data in an interface connected to a robot for manipulating the surgical tools. The robot incorporates extremely sensitive haptic feedback and is programmed to create the physical sensations of tissue resistance, cutting, and so on appropriate for the particular surgical procedure along the entire path of the operation. The visual data and the haptic program are coordinated with one another in the VR system. 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 the model and the 3-D stereo camera images are fused. 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-dimenstional CT and MRI by providing a precise determination of his tools' locations in the geography of the patient.[24] 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), which currently is headed by Richard Robb (figure 13.5).

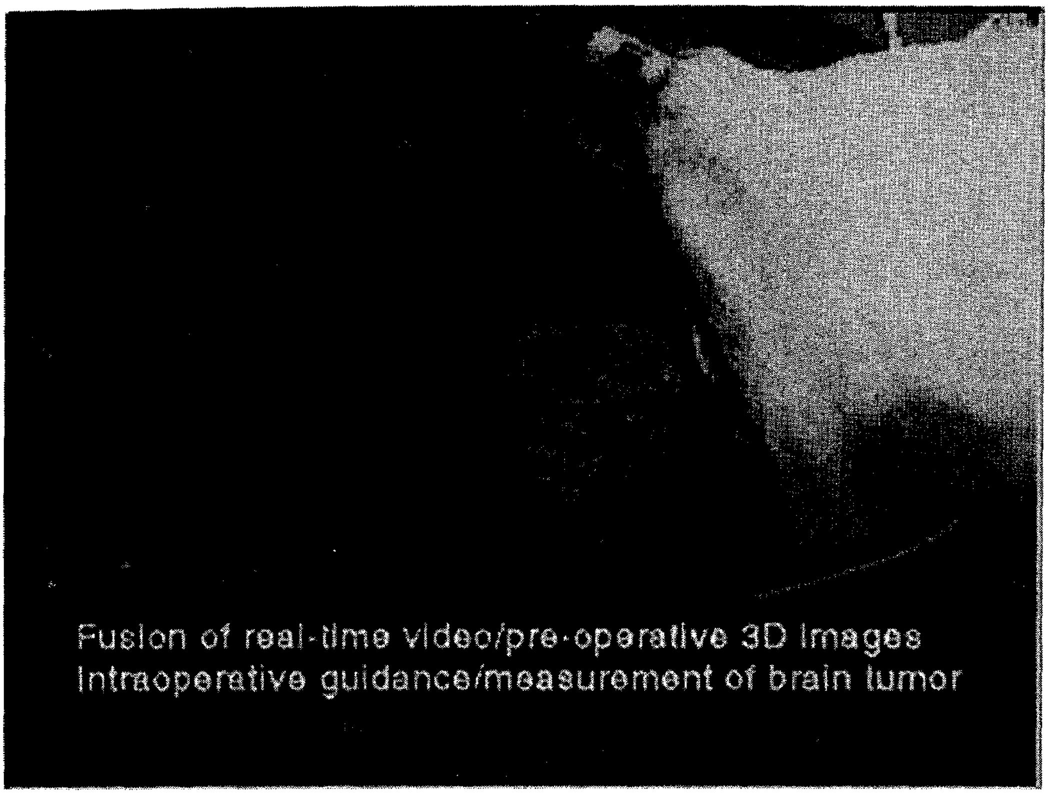



FIGURE 13.5. Synthetic vision using the Virtual Reality Assistant Program at the Mayo Clinic: superposition of direct video with graphics rendered from brain tumor data. Source: Richard Robb, Mayo Clinic: <http://www.mayo.edu/bir/guide.html>.

## TELEOPERATED MICROSURGICAL ROBOTS

One of the first systems to incorporate all these features in a surgical simulator was the microsurgical robot (MSR) developed for eye surgery by MIT robotics scientist Ian Hunter (see fig. 13.1 above). The MSR is particularly useful for illustrating our thesis that the ontology of the objects as well as the subject position of the surgeon are being transformed by new computer-mediated forms of communication and agency. At the same time, this work illustrates our point that the agency of the surgeon has never been so completely inscripted: the surgeon writes with a battery of three-dimensional authoring tools, and he must be constantly written into the operating scene.

The MSR system incorporated features described such as data acquisition by CT and MRI scanning, use of finite element modeling of the planned surgical procedure, and a force-reflecting haptic feedback system that enables the perception of tissue-cutting forces including those (scaleable between 3–100 times) that would normally be imperceptible if transmitted directly to the surgeon's hands. A distinctive feature of Hunter's MSR is its immersive virtual environment, which fuses video, touch, and sound into a virtual reality experience.

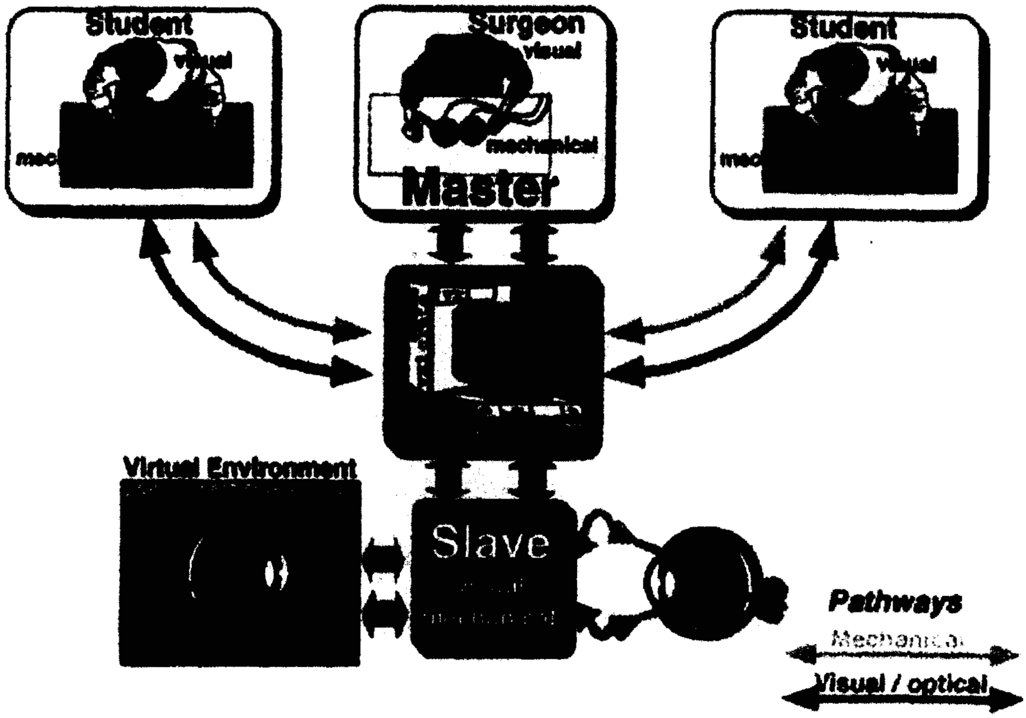



FIGURE 13.6. Ian Hunter's master-slave model. Source: Hunter, Doukoglou, et al., "A Teleoperated Microsurgical Robot," p. 271.

The MSR has three components: a microsurgical "master" and "slave," a virtual environment (VE), and an active mannequin (illustrated in the lower right-hand corner of figure 13.1). The master and slave subsystems (visual, auditory, and mechanical) communicate through a computer system that enhances and augments images, filters hand tremors, performs coordinate transformations, and runs safety checks. The surgeon wears a helmet (visual master) that controls the orientation of a stereo camera system (visual slave) that observes the surgery. Images from the stereo camera system are relayed back to the helmet (or to an adjacent screen) where the surgeon views them. In each hand the surgeon holds a pseudotool (a shaft shaped like a microsurgical scalpel) that projects from the left and right limbs of a force-reflecting interface (mechanical master). The master and slave components communicate via a fiber optical connection and can be located at different sites so long as signal degradation is avoided (figure 13.6).

The face for the virtual environment is created from the face of the patient with measurements made by a 3-D laser scanner and fitted by a parametric representation edited manually to add details not captured by the scan. These three-dimensional imaging systems are integrated into the slave unit itself, so that the patient about to be operated upon *and* the surgical model are mapped into the VE. Updates of the forces generated on the slave tool and the actual deformation of the tissue as it is cut are reflected back to the

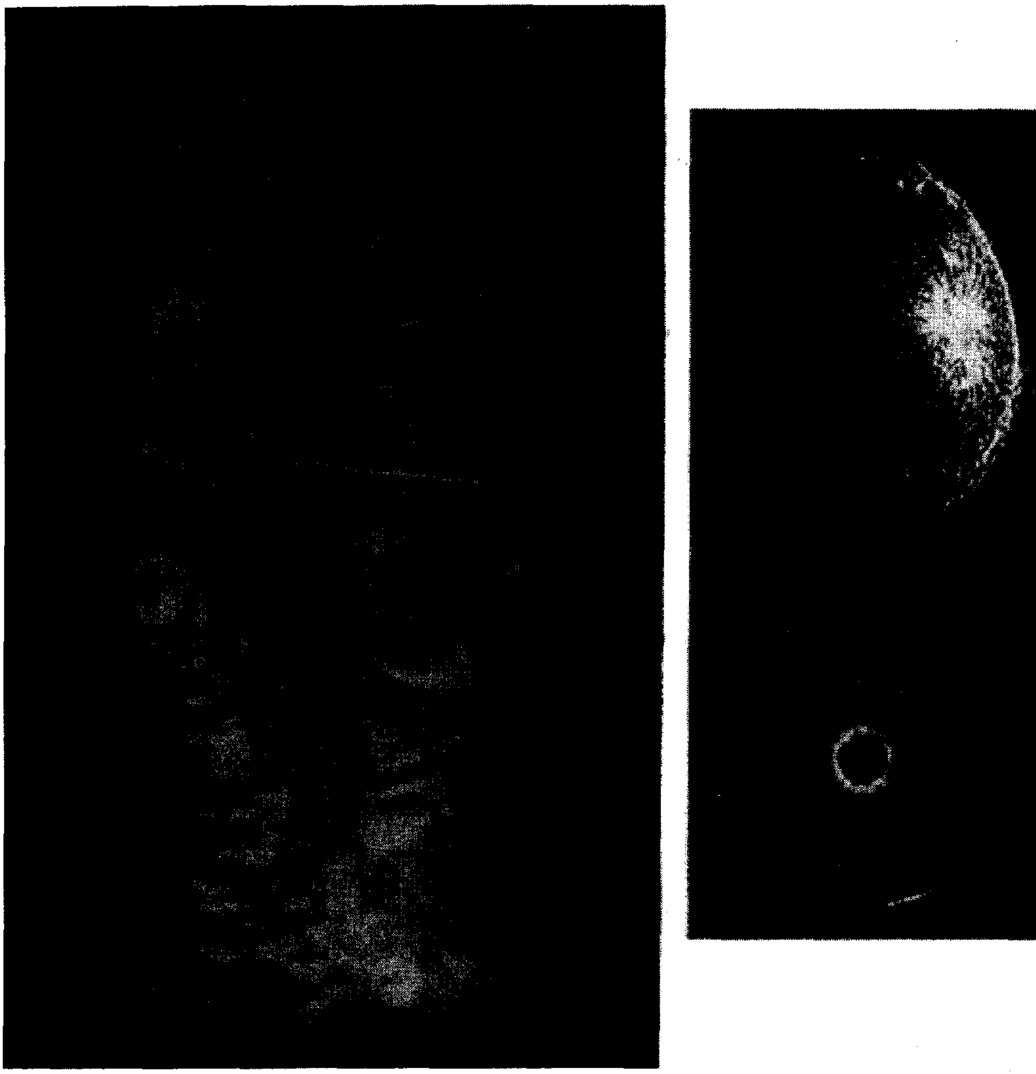


FIGURE 13.7. Ian Hunter finite element model of lens and cornea with realtime updating. Source: Ibid.

surgeon via the mechanical master. In this way virtual surgery is a realistic simulation, both seen and felt. In a final step for constructing the presurgical plan, a mannequin is produced from the computer model with polymers appropriately chosen to reflect the tensile properties of the tissue types making up the face or eye. The surgeon practicing on the surgical mannequin has the sense of cutting actual tissue.

One of the most innovative features of the MSR is its predictive capability. The geometric model of the eye is generated by a finite element model and incorporates physical properties of corneal and lens tissues that allow simulation of the change in the refracting power of the eye resulting from surgery. In this way, the effects of the surgical steps to be performed can be estimated in the planning stage and checked through comparative updates as the surgery proceeds (figure 13.7).

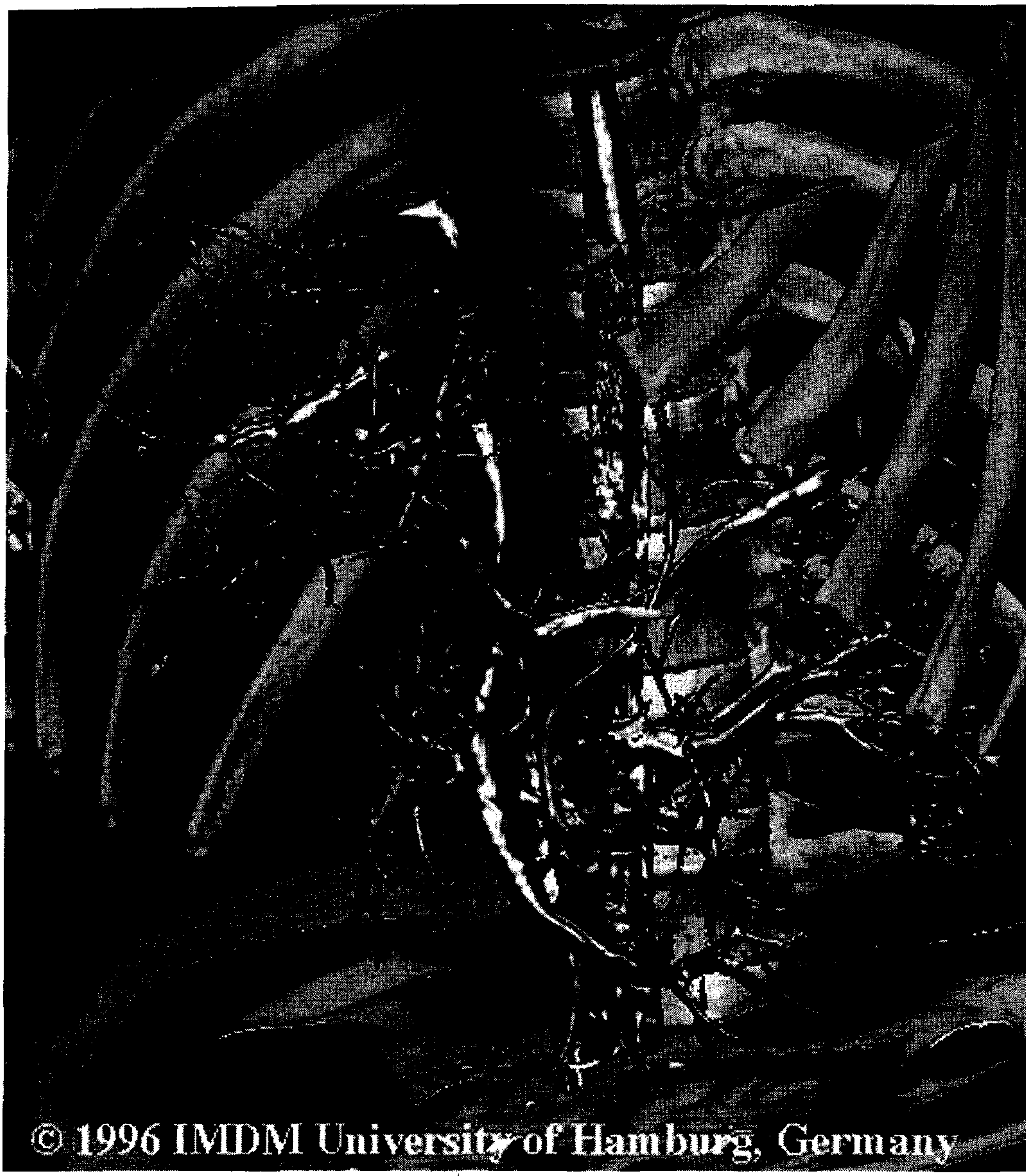
## VISUALIZATION

Major differences separate the computer-mediated surgical systems we have described from previous modes of surgery and experiences of the surgeon. Consider first the differences introduced by visualization and volume rendering. The visualizations employed in the new computer-mediated procedures are based on completely different methods than those that previous generations of surgeons relied upon. All earlier imaging modalities—X-rays, CAT scans, even MRIs—constructed two-dimensional views of anatomical objects. Although such images are useful for diagnosing many problems, direct access to the three-dimensional structure is preferable for surgical purposes, and in many cases for diagnosis.

Obviously, when planning a surgery on such organs, the ability to visualize the structure in its actual anatomical setting is crucial. A variety of powerful computer graphics tools have been developed to solve these problems by converting raw two-dimensional CAT or MRI data to three-dimensional volume. Among these tools is an algorithm called Marching Cubes.[25] This technique renders the surfaces of objects as a fine mesh of intersecting triangles and can provide very precise images of single structures useful for diagnosing tumors and other disease states of that specific structure, but it is less useful for understanding the context of surrounding anatomical structures. The anatomical context, however, is crucial for designing and implementing a surgery. For example, in designing an arterial stent graft it is important to know whether the planned stent is anatomically possible given the anatomy of the particular patient.

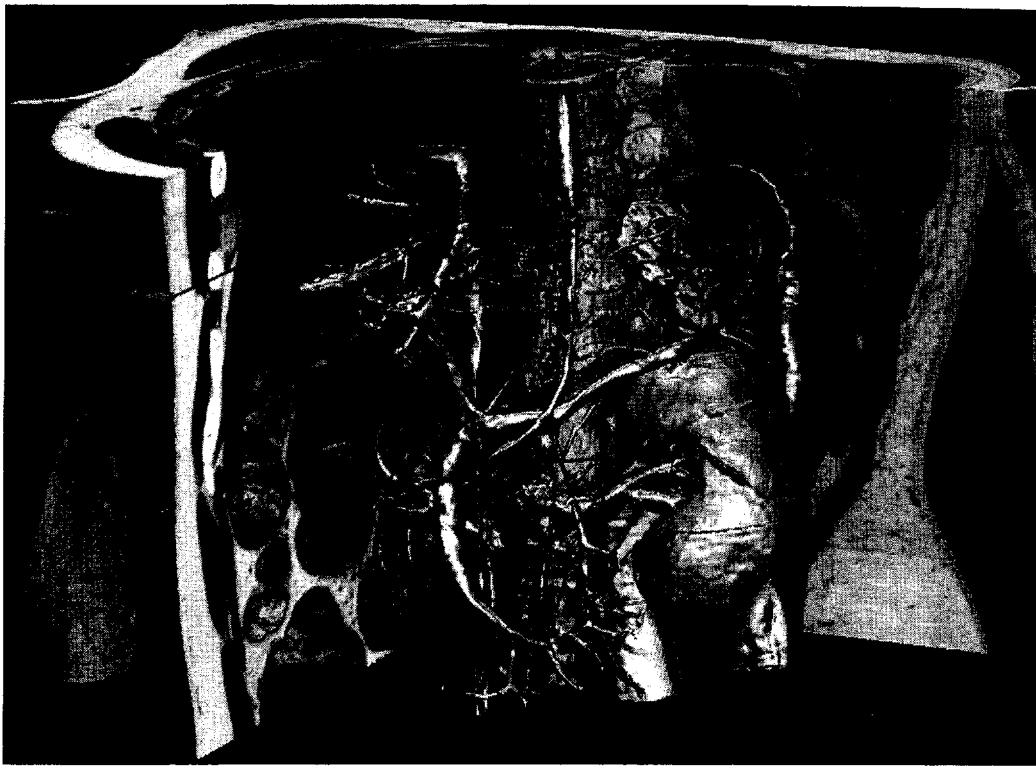
A significant alternative method to the meshing-triangle iso-surface representations generated by Marching Cubes is a method for tracing volume along an arbitrary ray. This rendering method was first developed at Pixar Studios as the basis of the Renderman system used to produce the cinematic animation effects in *Toy Story* and *Jurassic Park*. Other large visualization packages, including special hardware, such as graphics boards and accelerators, have been created to generate volume-rendered images directly from the input of "raw" (CAT, MRI, and ultrasound) imaging data. Among these programs are Voxel-Man, VoxelView, ARTMA, and several others.

The products of these imaging modalities differ from their predecessors in important ways. Much less expensive predecessor systems for representing three-dimensional anatomy, such as stereoscopic viewers and wax models dating back to the eighteenth century, also allowed the surgeon to rotate the structure and examine it from many angles. But these previous systems were all generalized anatomies rather than patient-specific, living anatomies, generated in real time. Moreover, ray-tracing volumetric rendering methods produce physically accurate representations of the internal volumes and




not just the surfaces, as with meshed surface triangle methods like Marching Cubes.

In a volume-rendered data set the surgeon sees *while inside the body* what is obstructing the path, as well as what is behind or next to it, from all directions, allowing more certain navigation through these interior spaces. A structure can be zoomed in on, viewed from any angle, even (unreal) angles impossible to see in any other way. Furthermore if some organ, tissue, or fluid is obstructing the view of the object the surgeon wants to see, the obstruction can be filtered out. This means, of course, that the new surgical object in the virtual environment has an "unnatural" appearance from a pre-virtual surgery point of view—surfaces are unnaturally colored, passageways



FIGURES 13.8a (facing page) and 13.8b: Voxel-Man volume rendering of internal organs. Source: Karl-Heinz Hoehne, "Voxel-Man 3D Navigator," in *Voxel-Man 3D Navigator—Inner Organs: Regional, Systemic and Radiological Anatomy* (New York: Springer Verlag, 2000).

such as the colon are "clean," and so on. But the objective is to isolate and manipulate the tissue in question.[26]

At this point we see some of the interesting ways in which workers in this new medium try to retain comfortable features of the medium being replaced. We see, for instance (figure 13.8) from Voxel-Man, elements, such as shading and texture, of pictorial realism in these images. In part, as Marching Cubes creators Lorensen and Cline note, this drive toward realism is due to the demands of physicians rather than radiologists. Physicians, Lorensen and Cline observed in their original discussion of the algorithm, lack the skills to interpolate three-dimensional images from two-dimensional radiological data.[27]

## THE SURGICAL BODY AS HYPERTEXT NARRATIVE

Although standard tropes of pictorial realism serve to familiarize readers of medical imagery with new visualization techniques, spatialized hypertextual strategies are also introduced in order to annotate volume elements trans-

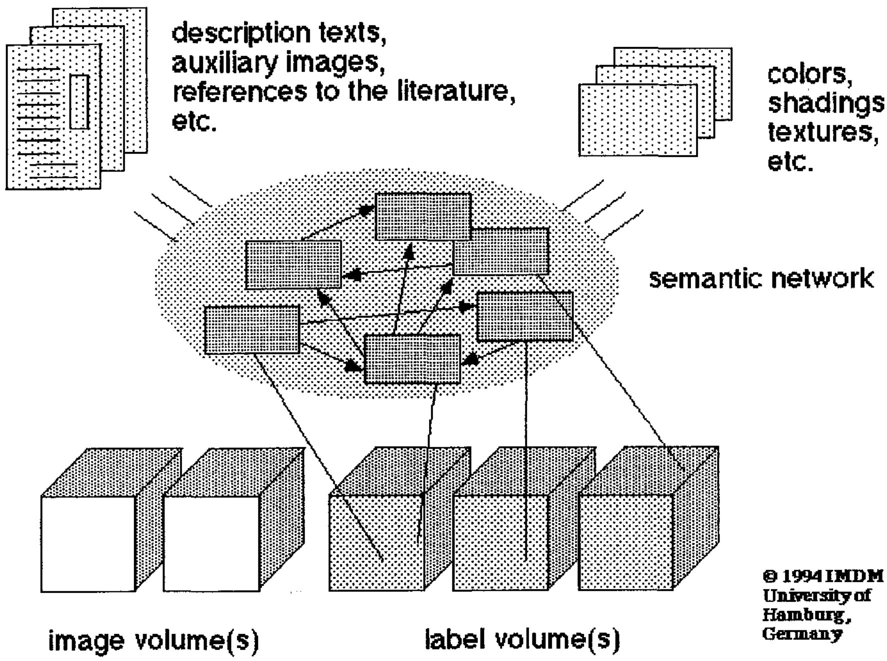



FIGURE 13.9. Voxel-Man intelligent volumes and semantic networks. Source: Andreas Pommert, Martin Reimer, Rainer Schubert, Thomas Schiemann, Ulf Tiede, and Karl-Heinz Hoehne, "Symbolic Modeling of Human Anatomy for Visualization and Simulation," in Richard A. Robb, ed., *Visualization in Biomedical Computing 1994* (Bellingham, Wash.: SPIE—The International Society for Optical Engineering, 1994), pp. 412–23.

forming them in the process to "intelligent volumes." Just as it would be mistaken to analogize new volume rendering methods with older methods of "imagining" the interior spaces of the body, it would also be a mistake to think of these intelligent hypertext volumes as the analog of earlier medical atlases. Text-bound atlases are limited in the ways they present anatomy by the particular emphasis—physiological, anatomical, or systemic—of the persons constructing the atlas. Multiple perspectives are difficult to combine. Ordinarily these are further limited in dimensionality, such as sagital, dorsal, and so on. The intelligent volumes of hypertext atlases are context-specific down to the level of volume elements (figure 13.9).

The Voxel-Man project 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 symbolic model of the human body is attached, a complete atlas with textual description of whatever detail necessary for every volume element in an anatomical structure. 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 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. Patient-specific data for that particular region, such as the specific frames of MRI or CAT data used to construct the simulation, can also be included.

Such intelligent volumes are not only 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 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. In this form of augmented reality, we encounter a narratology that would have delighted Julian Greimas and Paul Ricoeur: a non-chronological spatial distribution of actants generates both plots and characters in this medical narrative.[28]

## DISCOURSE NETWORKS 2000: REGIMES OF THE COBOT

The microsurgical robots we have described are particularly designed to enable delicate and intricate surgeries, such as stereotactic neurosurgery and many brain surgeries, otherwise limited by the capabilities of the human hand and by the workspace available. In addition, the tracking capabilities of the system's teleoperator extensions allow a surgical tool to follow precisely a moving organ, such as a moving eye or beating heart. An imaging system mounted on the robot limb with the same axis of rotation as the eye, for example, is locked-on via servocontrol so that the surgeon sees a stabilized eye in the virtual environment and can proceed with the required surgery. Such extensions allow heart surgery without forcing the heart to stop.

Entangled economic, disciplinary, and political histories are bringing about, in the Foucaultian sense, the constitution of a new discursive formation. The shift in the subject positions *author* and *surgeon* can be mapped nicely along the dimensions of responsibility and subversion Foucault noted as central to establishing the author function.[29] As Elliot Freidson, Magali Larson, Charles Rosenberg, and Paul Starr have variously argued, the autonomy of the physician—the ability to act as a free, creative agent guided by the standards of a professional community—was predicated on a contract with society in which the person authorized to practice surgery was held personally liable, both financially and criminally, for malpractice and professional misconduct.[30] This near-absolute autonomy of the physician reached its zenith in the early decades of the twentieth century following the Flexner Reforms. But as the practice of medicine has become more technology-intensive, moving into hospital-clinics with large infrastructures of technical support beyond the reach of physicians to own and manage themselves, the autonomy of the physician has been limited. Within the health maintenance organization (HMO) at the center of the modern health-care industry the physician is a large ticket item, but also just another employee. Along with this deterioration of the physician's autonomy has come a redistribution of responsibility for acts of malpractice. The health-care organization or hospital in which the procedure is performed and without whose support staff and technology the procedure could not have been performed has come to be named codefendant in malpractice cases.

In the surgical domain of VR-interfaces and real-time volume rendering, this distribution of responsibility goes several steps further: The responsible agents are a different cast of characters. For instance, up until now, the physician has depended on a radiologist to read the sequence of x-rays or an MRI. The radiologist produces a written report with a diagnosis for the physician, and the physician processes this written account together with the images supplied to produce an imaginary representation, the basis for intervention. In this system, mistakes in reading the imaging data are the responsibility of the radiologist. All sorts of conventions come into play in making a diagnosis, such as the orientation of the patient's body on the imaging system, the direction one reads the image, and so forth. In new real-time imaging systems, however, the radiologist is replaced by a software package that automatically segments the data, giving it structure. The radiologist is displaced by another set of agents: namely, the authors of the code. And as we well know, a traditional problem is the unprovability of software.[31] Can we tell who is responsible for a coding error? Not a simple matter. Similarly, in the telerobotics systems we have examined, 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 three-dimensional medical viewer—in combination with echocardiograms, CAT scans, and MRI images of his 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, the surgeon "saw" structures he would see as he performed the actual surgery, a quasi-virtual surgical template in his imagination. 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 VR surgical theater we are describing, a much more concrete discursive setting appears, one of stainless steel clamps, CPU's and video monitors. This networked theater is shared by the imagining surgeon and imagining colleagues brought together by the technologies of telepresence. But the theater is filled also with hyperreal colleagues, constructed by programmers from a constellation of software companies. Software-generated models and data visualizations project back onto the patient's body and into the surgeon's computer-mediated vision. But there is one further step here beyond the "mental" agency of the subject in Foucault's discourse network. In our case, the imaginary functions carried out by Foucault's ethereal discursive subject are rendered literal. They are completely externalized in computational algorithms for data segmentation, volume rendering, and graphical presentation.

More than vision is at stake in computer-mediated surgery. Discourse networks, of whatever technical constitution, are as much social constructs forged from controversy and labor as they are material configurations. We have been pointing to the "interests" of physicians, health maintenance organizations, and ordinary patients in the construction of the desire for these technologies. Consider a recent development in the field: gesture macros and speech macros. Under the pressures of documenting medical procedures for reimbursement by HMOs, some physicians have sought ways to say more with less. Using speech-recognition systems, the physician needs to utter only certain phrases into a recognizer, from which the system constructs many pages of "written" documentation of the medical performance according to the templates of legal language.[32] These speech macros mediate, via computational logic, the surgeon's self-presentation, and they inscribe the surgeon into the legal and authorial structures of the new collective medical agent. 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. One could, for instance, implement a version of the Oregon Health Plan, which ranks 700 diagnoses and treatments in order of importance. Items below line 587 are disallowed.[33] In the future, the appropriate constraints and efficiency measures could be preprogrammed into the surgical treatment planning simulator.

A glimpse of the next step in this dispersion of agency and its accompanying surveillance may be offered by the work of Michael Peshkin and Edward Colgate in the robotics laboratory at Northwestern University. Peshkin and Colgate are building a Force Reflective Endoscopic Grasper, a modification of surgical endoscopic telesurgical robots for use in automobile manufacturing. Peshkin and his colleagues are modifying these surgical systems to build *cobots*. Traditional robots supply the power and mobility and the human operator provides guidance. Cobots reverse this relationship. Cobots dispense with the powerful motors that drive conventional robots—and make robots dangerous. Instead, the primary function of the cobot is guidance of the human operator, its secondary function to offer support against gravity. According to Peshkin: "The human worker supplies all the force necessary to move the component, while taking advantage of the cobot's guidance to push it along quickly and easily without fear of collisions. The future may hold cobots of other shapes. . . . [T]he benefit of conventional robots is not their strength or autonomy, but rather the fact that they are directed by computers. . . . You can think of a cobot as a physical interface for a person to collaborate with a computer."[34]

Noting that computer-assisted surgery shares the features of necessary cooperation between human and machine found in automobile assembly, Peshkin and Colgate are also designing an arm-like cobot to be used in computer-assisted surgery. So we are only a few lab benches away from introducing cobotic agency into the severed mechanical stem of the surgeon's tool, thereby inserting a computationally mediated apparatus of discipline between the surgeon's hand and the patient's flesh.

40. Ascott, Interview with the author, May 25, 1995, Bristol.
41. Ascott, "Behaviourist Art."
42. Kristine Stiles, "Process," in Stiles and Selz, *Theories*, p. 586.
43. Ascott, "Behaviourist Art," p. 25.
44. Ibid., pp. 28–29.
45. H. Ross Ashby, "Design for an Intelligence Amplifier," in Claude E. Shannon and J. McCarthy, eds., *Automata Studies* (Princeton: Princeton University Press, 1956), pp. 215–34. In regard to computers as interactive behavioral systems, Ascott noted his admiration for the work of Gustav Metzger, whom he knew in London, and Nicolas Schöffer. Interview with Ascott, May 25, 1995, Bristol.
46. Ascott, "Behaviourist Art," p. 47.
47. Roy Ascott, "The Cybernetic Stance: My Process and Purpose," *Leonardo* 1 (1968), 106.

## PART 5 INTRODUCTION

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2. Hans Moravec, *Robot: Mere Machine to Transcendent Mind* (Oxford: Oxford University Press, 1999); Ray Kurzweil, *The Age Of Spiritual Machines* (New York: Penguin, 1999); Bill Joy, "Why the Future Doesn't Need Us," *Wired Magazine* (April 8, 2000): <http://www.wired.com/wired/archive/8.04/joy.html>.

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10. Ibid., p. 102.

11. Ibid., p. 103.

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34. See <http://othello.mech.nwu.edu/peshkin/cobot/>. Greg Paula, "Cobots for the Assembly Line," *Mechanical Engineering*, October, 1997: <http://www.memagazine.org/contents/current/features/cobots/cobots.html>. Prasad Akella, Michael Peshkin, and Edward Colgate, "Cobots: A new generation of assembly tools

for the line worker," *SPIE Robotics and Machine Perception International Technical Working Group Newsletter* (April 1997): <http://othello.mech.nwu.edu/peshkin/cobot/spie/spie.html>.

## CHAPTER 14

1. I introduce the notion of *transmorphosis* to describe an operation between-and-above *transformation* and *metamorphosis.* For more on the latter concept, see Bruce Clarke, *Allegories of Writing: The Subject of Metamorphosis* (Albany: SUNY Press, 1995). *Allomorphosis*, *xenomorphosis*, and *exomorphosis* belong to the same cluster of meanings I intend and are useful in describing species of the production of the alien. *Diamorphosis* and *paramorphosis* are related concepts describing other aspects of morphosis–genesis that range from the pedagogical to the monstrous. *Transmorphosis* is intended to collect these various notions of formation and to call attention to their transversal connection to the alien. That the word *transmorphosis* is a linguistic hybrid, combining the Latin prefix *trans-* with the Greek *morphe*, is only appropriate.

2. See Naomi Matsunaga, ed., *Transarchitectures in Cyberspace: Ten Architects who Simulate the World* (Tokyo: Nikkei Architecture, 1998); and Marcos Novak, "Next Babylon, Soft Babylon: (Trans)Architecture Is an Algorithm to Play In," *Architects in Cyberspace II*, ed. Neil Spiller, in *Architectural Design Profile* 136 (November–December 1998), and "Transarchitectures and Hypersurfaces: Operations of Transmodernity," *Hypersurface Architecture*, ed. Stephen Perrella, in *Architectural Design Profile* 133 (May–June 1998).

3. Peter Anders, *Envisioning Cyberspace: Designing 3D Electronic Spaces* (New York: McGraw-Hill, 1999).

4. For more on Maxwell's Demon, see the section "Statistical Mechanics and Maxwell's Demon" on p. 23 in this volume.

5. Iannis Xenakis, *Formalized Music: Thought and Mathematics in Music*, rev. ed. (Stuyvesant, N.Y.: Pendragon Press, 1992).

6. Images of various elements of Hoberman's installation appear throughout Peter Galison and Caroline Jones, ed., *Picturing Science, Producing Art* (New York: Routledge, 1998).

7. Ray Kurzweil, *The Age of Spiritual Machines: When Computers Exceed Human Intelligence* (New York: Viking Press, 1999).

8. See N. Katherine Hayles, *How We Became Posthuman: Virtual Bodies in Cybernetics, Literature, and Informatics* (Chicago: University of Chicago Press, 1999).

9. On the application of voxels in virtual imaging programs for the surgical theater, see the essay by Lenoir and Sha (chapter 13) in this section.

10. B. C. Crandall, ed., *Nanotechnology: Molecular Speculations on Global Abundance* (Cambridge, Mass.: MIT Press, 1997).

11. Brian R. Greene discusses the nanoscales at which quantum mechanics and the hypothetical behavior of "super strings" occur, in *The Elegant Universe: Super-*