There is a revolution taking place in the modern practice of medicine—particularly in the field of surgery. This surgical revolution has evolved out of the so-called “information age” of the late 20th century and early 21st century. We are witnessing an explosion in newer technologies that combine the biological, physical, and information sciences into systems that enhance technological performance well beyond previous limitations.

The essence of the information age was first proposed in 1995 by computer scientist Nicholas Negroponte, PhD, of the Massachusetts Institute of Technology in his book, Being Digital. Using information science as a tool, Dr Negroponte developed the idea of “bits instead of atoms” as a driver of technological change. He suggested that these bits, or units of computer information, could be applied in medicine to improve the understanding of the human body and the healthcare of patients.

One of the best-known applications of information science in medicine has been the National Library of Medicine’s Visible Human Project, a digital image library of volumetric data representing complete, normal male and female anatomy. In this project, high-resolution, three-dimensional (3D) representations of the bodies of a man and woman were created by combining computer-generated images derived from computed tomography (CT) scans and magnetic resonance imaging (MRI) scans. These 3D digital representations can be manipulated on a computer screen to study aspects of internal anatomy from any angle at various levels of detail.

The current trend in surgery toward minimally invasive and noninvasive therapeutic procedures is another result of newer technologies generated by information science. This trend represents a switch from direct, hands-on surgical approaches to indirect, “hands-off” approaches (eg, laparoscopic, catheter-based, robot-aided, and computer-aided procedures). This switch coincides with moves by surgeons from unimodal therapy (eg, resection and reconstruction) to multimodal therapy (eg, biologically tagged, image-guided, and dexterity-enhanced procedures).

In the present article, we review a number of currently available technologies that are reshaping surgical procedures in the United States. Changes in the areas of preoperative diagnostics, preoperative planning of surgery (including surgical simulation), and intraoperative navigation (including augmented reality) are presented. We also look into the future of surgical care based on projected technological advancements, anticipated patient demands, and economic reality.

Applications of Computer Technology

The accelerated growth of computer technology that began in the 1970s has paved the way for many dramatic changes in medicine. Included in this growth have been such advances in medical imaging technology as ultrasound, CT scanning, and MRI scanning. Computer-based digital imaging technology has become an integral part of surgical therapy through its integration at all levels of surgical care. Departure from traditional two-dimensional (2D) imaging (ie, radiographs) to the 3D visualizations available through such technologies as CT scanning and virtual reality has offered effective new tools for preoperative diagnostics and planning, intraoperative navigation, and robotic surgery (Figure 1).

Preoperative Diagnostics

Virtual reality refers to simulations of real or imagined environments that can be experienced in three dimensions and explored interactively at a computer while using a mouse or other hand controls. This technology—in the form of computer-based surgical simulations—is beginning to play a role in preoperative surgical diagnostics, particularly in virtual endoscopic applications.

Because virtual endoscopy is less invasive, safer, and possibly less expensive than standard endoscopy, it may soon become the preferred diagnostic method for the evaluation of multiorgan systems. Current applications of virtual endoscopy in preoperative diagnostics include bronchoscopy, colonoscopy, cystoscopy, and gastroscopy. Most of the current clinical trials and research in this area involve virtual colonoscopy, which is also called CT colonography.
In virtual colonoscopy, the technique of spiral CT is combined with virtual reality computer technology to provide—within one minute—a diagnostic examination of the patient’s large bowel, including views of the colonic mucosa. In the spiral CT scan, numerous cross-sectional views of the colon are rapidly integrated by computer to create a detailed 3D representation of the entire colon. This 3D representation can then be manipulated on the computer screen using sophisticated software that allows the physician to quickly and accurately inspect any part of the colon.

Clinical results of virtual colonoscopy suggest that it surpasses the diagnostic usefulness of barium enema and approaches the sensitivity of conventional fiberoptic colonoscopy in the detection of polyps and other masses greater than 5 mm in size. However, current limitations of virtual colonoscopy include the inability to visualize actual texture or color. In addition, physicians must take care to recognize certain anomalies in virtual colonoscopy resulting from incomplete bowel preparation.

The accuracy and usefulness of virtual colonoscopy and other virtual endoscopic procedures are expected to surpass that of standard endoscopy as the level of image resolution improves and as methods for incorporating texture and color are developed. Although noninvasive virtual endoscopy may eventually replace minimally invasive standard endoscopy for diagnostic procedures, standard endoscopy will probably continue to be required for therapeutic purposes, such as biopsies.

Preoperative Planning and Surgical Simulation

Preoperative surgical planning has traditionally taken place with the aid of radiographs, ultrasound, and other 2D imaging techniques. Although the development of 3D digitized medical images has been helpful in preoperative planning, the use of these images for the detection of lesions and the localization of tissues and vessels has previously been limited. Now, however, 3D medical images are being used in virtual reality applications, making it possible to create realistic preoperative surgical simulations. Computer-based surgical simulations not only aid clinicians in training and surgical rehearsal settings, they also can be used to guide the execution of surgical plans.

During preoperative planning, the simulation of complex surgical procedures with virtual reality software, including the 3D reconstruction of anatomic images, can help clinicians create detailed intervention plans. This type of computer-assisted planning has been applied mostly in such specialty areas as orthopedics, craniofacial surgery, and neurosurgery.

Delp and Zajac used a virtual reality computer model of the lower extremities to simulate the lengthening of musculotendon complexes and the effects of this lengthening on gait. They noted that such simulations would be useful for developing interventions for gait disorders. In the field of craniofacial surgery, Altobelli et al integrated 2D CT data of normal craniofacial anatomy with 3D reconstructions of patients’ craniofacial deformities. The simulations derived from this integration allowed the researchers to better evaluate the patients’ deformities, which assisted in the design and planning of corrective surgical procedures. Several case studies by Kikinis et al involved the use of 3D preoperative simulation and interactive computer-based manipulation to gather information about patients’ brain lesions that was otherwise inaccessible. This information aided in the surgical removal of the lesions.

The use of virtual reality and 3D imaging in the reconstruction of soft tissues during preparation for general surgery is complicated by the mobility of the body’s organs and the absence of a firm, bony reference frame. However, newer simulation systems are addressing these problems. For example, Marescaux et al used cross-sectional image data from the Visible Human Project to develop an interactive 3D computer model of the liver in which this complex organ could be clearly visualized and manipulated. They concluded that this kind of computer simulation could greatly aid in surgical planning and improve the efficiency of hepatic surgical interventions. Lamade et al also developed a 3D computer-based planning system for hepatic surgery. After testing the system on “virtual patients” with liver tumors, Lamade et al concluded that 3D reconstruction of the liver can lead to significant improvement in tumor localization and surgical planning.

Beyond planning for anatomic interventions, preoperative virtual reality is also being used to predict the physiologic responses to therapy. Using a comprehensive computerized framework for advanced imaging and flow simulation, Taylor et al modeled the fluid dynamics of the aorta and lower extremities to predict the outcomes of various vascular interventions. By using this computer simulation to compare the

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**Figure 1.** Computer technology has provided a number of advanced surgical techniques that are effective tools for preoperative diagnostics and planning, intraoperative navigation, and robotic surgery.
predicted vascular flow rates of a number of different vascular interventions, the most efficient procedure could be chosen for each patient.15

**Intraoperative Navigation and Augmented Reality**

Intraoperative navigation, or image guidance, is a system for navigating through surgical procedures with the aid of anatomic images of the patient, such as radiographs, ultrasound images, CT scans, or MRI scans. This system has been used for many years, especially in the field of neurosurgery.16

Today, intraoperative navigation is being combined with augmented reality, in which data from two frames of reference are fused to enhance the visualization and understanding of the anatomic information.16 The two frames of reference used in augmented reality are a 3D reference image of part of a body (which may be the patient’s own body or a body used only for reference purposes) and a real-time image of the corresponding part of the patient’s anatomy. The reference image can be superimposed onto the real-time image. The anatomic features of interest are labeled in the reference image so that, when the reference image is superimposed onto the real-time image, the surgeon finds them easier to identify and examine.

Augmented reality has been used successfully in a number of surgical procedures. For example, by superimposing preoperative MRI scans with intraoperative MRI scans, Jolesz9 demonstrated that optimal localization and needle placement could be achieved for biopsies of deep-seated brain lesions. Such reports indicate that the use of advanced image-guided interventions has the potential to result in improved safety, efficiency, and cost-effectiveness of surgical procedures.9

**Robotic Surgery and Telesurgery**

Laparoscopic surgery is a type of intervention that may be considered a “transitional technology,” bridging the gap between conventional surgery and more advanced forms of surgery. From laparoscopic surgery has evolved the revolutionary technology of robotic surgery, a computer-aided and image-guided intervention in which the surgeon has limited contact with either the patient’s tissues or the surgical instruments.17 Instead, the surgeon works at a computer station, operating a set of finger controls while viewing an interactive 3D representation of the intervention. The surgeon’s finger movements are translated into actual instrument manipulation by a multi-armed robotic system that moves over the patient in the operating room.17

A sophisticated computer robotics system can translate the surgeon’s finger and hand motions into magnified, yet more precise, movements of the robotic surgical tools, with hand and finger tremors filtered out. In addition, motion-tracking software can be used to stabilize the appearance of moving organs on the computer monitor to enable the surgeon to see the surgical site more clearly.18 Research suggests that this technology can result in levels of technical precision and patient safety beyond that achieved with conventional surgery.18 Several favorable clinical reports describing robotic surgical systems have been published, including reports on systems for laparoscopic cholecystectomy,19,20 laparoscopic tubal anastomosis,21 radical prostatectomy,22 and cardiac surgery.23

Telesurgery, or remote surgery, is the application of robotic surgery across long distances—in fact, the surgeon and patient may be thousands of miles apart.17 This type of surgery is made possible by the transmission of digital data by high-speed telecommunications technology. In 2002, Marescaux et al24 reported the first case of telesurgery performed on a human. In this case, which took place in September 2001, surgeons in New York City performed a laparoscopic cholecystectomy on a 68-year-old woman in Strasbourg, France.17,24 Although a long time lag in data transmission had previously been anticipated as a barrier to the application of telesurgery, the New York surgeons reported a mean time lag of only 155 milliseconds—despite the fact that the data traveled a round-trip distance of 14,000 km (8700 mi). The surgeons stated that they perceived the remote robotic procedure, which lasted 54 minutes, as both safe and reliable.24

Robotic systems and telesurgery allow for the total integration of all stages of surgical care. Preoperative diagnostics, preoperative planning and surgical rehearsal, intraoperative navigation, decision support, objective assessment, and postoperative follow-up can become a continuum of care with the use of robotics.18 Data fusion and real-time video images may be used to track the surgeon’s hand motions, which are immediately compared with previous surgical performances that are digitally stored in the computer system, including the “ideal” performance for that particular technique. The robotic system alerts the surgeon to any deviations from the usual or ideal performance, providing a constant source of decision support.18 Thus, the ability to rehearse and record a surgical technique offers the opportunity of using the ideal performance as a standard for assessment, surgical privileging, and certification.

**Operating Room of the Future**

The revolutionary technological developments occurring today in surgical care provide hints at the even more amazing advancements that the future may hold. Framed by technology and directed by medical economics and patient demand, the operating room of the future will undoubtedly be dramatically different in both appearance and function from the operating room of today. A greater emphasis on integrated systems will provide for the streamlining of operating room personnel and materials management (Figure 2). In a personal account in 2004 of the historic evolution of robotic surgery, Richard M. Satava, MD,25,26 a professor at the University of Washington in Seattle who has conducted extensive research in robotic surgery, virtual reality, and computer simulation, shared the following vision of the operating room of the future:
Many of the current and projected technological advancements in surgical care come with profound socioeconomic or ethical implications. Some of these implications may be perceived as beneficial, while the effects of others may be more open to debate.

With the use of remote robot-assisted surgery, geographic location no longer has to be an impediment to the type of surgical treatment available to a population. Telesurgery, should it become more common, would allow for the increased availability in remote areas of access to expert surgeons from the best institutions around the world. In developing countries, this increased and improved access could prove to be of great benefit, making it possible for people to receive surgical care that would otherwise not be available to them. However, to take advantage of this possibility, these countries would need access to high-speed telecommunications technology—which is still lacking in many undeveloped regions of the world.

Telesurgery also holds great promise for medical education. With the ability that telesurgery provides of making the best training widely available, errors caused by surgeon inexperience could be reduced, resulting in an improvement in the nationwide standard of surgical care.\textsuperscript{22}

Despite the many bright promises of new medical technology, the technology carries a serious risk—the risk of spreading faster than the medical profession can react to it, with surgeons facing the challenge of learning new skills but not having objective ways to assess competency in those skills. Therefore, with the projected growth in medical technology, new approaches to education, assessment, and training will be required. We are reminded of the accelerated development of laparoscopic surgery during the 1990s, when surgeons had little time to feel completely competent with the procedure before they felt compelled to incorporate it into their practices.\textsuperscript{18}

Without proven efficacy for surgical procedures based on new technology, issues of billing and insurance reimbursement for those procedures can become a problem. Even after objective methods to measure competency have been developed, the need for surgeons to repeatedly practice the new techniques to reach the benchmark levels of performance could result in high quality, but very costly, surgical procedures. These costs could prohibit much of the population from using the new procedures.

**Conclusion**

The technological advancements in surgical care and other fields of medicine that have occurred since the late 20th century are forcing surgeons to re-evaluate the practice of surgery. Many of these advancements are related to technological breakthroughs in information science. We find ourselves in the middle of a transition period that will lead to fundamental changes in the practice of surgery. Despite these changes, however, surgery will not be replaced; rather, it will mature as new technologies are validated.

Several challenges face the surgeon during this transition period. As the rate of change in technology outpaces the ability of surgeons to respond in a timely manner, the need for
stringent evaluation through evidence-based outcomes is essential. Surgeons must look at these emerging technologies with an open, yet critical, mind. They must be prepared to embrace change while remembering their responsibilities as stewards for their patients.

The surgeon of today must respond to ongoing technological changes through open discussion and debate on a national level. If not, the medical profession will relinquish far-reaching decisions on these important matters to lawyers, politicians, and others with limited understanding of science and humanistic needs, and rules and regulations will be established based on their personal, societal, or political agendas. As technological change happens and discussion and debate continue, the science will wait for no one. Surgeons must position themselves today to control the medical technologies that emerge tomorrow.

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