Surg Endosc (2003) 17: 104–107
DOI: 10.1007/s00464-002-0018-x

Surgical Endoscopy
and Other Interventional Techniques

Disruptive visions

The operating room of the future

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Received: 11 July 2002/Accepted: 15 July 2002/Online publication: 4 October 2002

Abstract
A number of concepts have been advocated for the next generation operating room based on some inadequacies of the current systems. Most have focused on removing excess tubes and wiring, others on information systems or robotics. An analysis of other industries, a projected direction of current technologies, a focus on the importance of integrated information systems, and a serious consideration of emerging basic technologies suggest a significantly different approach.

Key words: Operating room of the future — Robotics — Bioinformatics — Surgical technologies

The operating room began with a kitchen table, and has progressed over the centuries to a sophisticated, specialized room within a suite that has evolved through iterative change. One of the most recent changes has been forced by the introduction of laparoscopic surgery. This change came suddenly with little thought of the room in which the procedures were conducted. The immediate, pragmatic solution was to add the necessary equipment, removing whatever possible to reduce the clutter. This resulted in the current inefficiencies that exist today.

There have been a few attempts to improve on the current situation, with modest success. The more advanced systems have moved most of the equipment, wires, and tubes off the floor and suspended them from the ceiling [4]. With the introduction of robotic surgery, there have been a number of efforts at integrating the systems, including voice activation [5]. Yet despite this progress, there has been no change in the concept of the operating room.

The technological change has been so rapid that it is necessary to look at the operating room from a completely different perspective. As previously stated, laparoscopic surgery is a transition technology to robotic and image-guided surgery [9]. In addition, it is necessary to look at the direction the entire spectrum of surgical technologies is going within the Information Age. Finally, many solutions can be discovered by looking at other disciplines that have used robotics even more successfully than health care. Combining these factors can result in a new concept of an operating room.

The surgical community has responded to the rapid rate of change by reacting with small changes instead of rethinking the entire discipline of surgery. However, the new technologies have engendered such a huge change that improving on what is available is not the answer. It is essential to seek out these new technologies and implement them in a fundamentally different manner.

One of the most important aspects is to realize that laparoscopic surgery is not what the future of surgery will be. A number of procedures will continue to be performed laparoscopically, but the majority will be performed through computer assistance, whether robotic, computer-enhanced, or image-guided. The reason is unambiguous. Robotic or computer-assisted surgery is an information (and Information Age) technology, and laparoscopic surgery is mechanical (Industrial Age) technology. Thus, total integration of the laparoscopic system with all the other supportive functions is not possible. The achievement of surgical systems integration requires an information-based approach.

The key to understanding the future of surgery is to understand that information technology is the underlying support structure. This includes, but is not limited to, robots, computers, networking, communications, digital imaging, databases, decision support systems, assessment tools, and automatic error detection, to name a few. In cyberspace, there is no difference between a

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robot, a database, and an imaging system. A robot is an information system with “arms;” a database is an information system with “memory;” a digital imaging system (computed tomography [CT], magnetic resonance imaging [MRI], ultrasound) is an information system with “eyes;” and so forth. Because they all are information systems, they can be totally integrated to support the entire surgical and health care enterprise. Also, for the first time, the “product” of health care, the patient, is becoming an information system, through total body scanning and the holographic electronic medical record or “holomer” [8]. Thus, a robot can interact with a CT scan, but a laparoscopic instrument cannot.

In analyzing other disciplines such as aviation, automobile, microchip, and the like, it becomes apparent that those industries have the template for the processes of the Information Age. An analogy can be made between industry and health care (the health care analog of information technology will be in parentheses). For example, in the automotive industry, the product is the automobile (as compared with the patient in the health care industry). Initially, a virtual representation in computer-aided design (CAD) of the automobile is created (for patients, a total body scan). All the various parts are then analyzed, virtually assembled, and the design is refined until it is perfected (preoperative planning) followed by virtual testing (surgical rehearsal). Then throughout the manufacturing process, using computer-aided manufacturing (CAM) of the real automobile (intraoperative navigation), the most precise result is obtained by using imaging with automatic target acquisition and recognition (image-guided surgery). On the assembly line (operating room), the robots do not have humans changing the tools. There are automatic tool changers (scrub nurse), and the parts to be assembled are “handed” by an automatic inventory dispenser (circulating nurse). The merging of all these functions and machines is possible through their common information infrastructure. In the health care world, all these functions can be integrated through the robotic system, which is controlled by the surgeon (Fig. 1). In industry, training to control and supervise the robots occurs on a simulator. The emergence of surgical simulators can provide analogous training for surgeons.

There are other complementary technologies that can be integrated into the revolutionary concept. Despite the most valiant efforts, it is literally impossible to make an operating room sterile, yet the computer chip industry has clean rooms that are orders of magnitude more sterile. A recent device, the Life Support for Trauma and Transport (LSTAT), is an entire intensive care unit with intelligent monitoring [7]. This device is used by the military from battlefield wounding to emergency room to operating room to recovery room, with continuous monitoring of vital signs and control of respiration as well as other vital functions. It also should be noted that the pharmacies at most large medical centers have replaced the pharmacy technician (who usually counted out the pills, placed them in a bottle, labeled the bottle, and then reordered more pills) with an automatic pill dispenser.

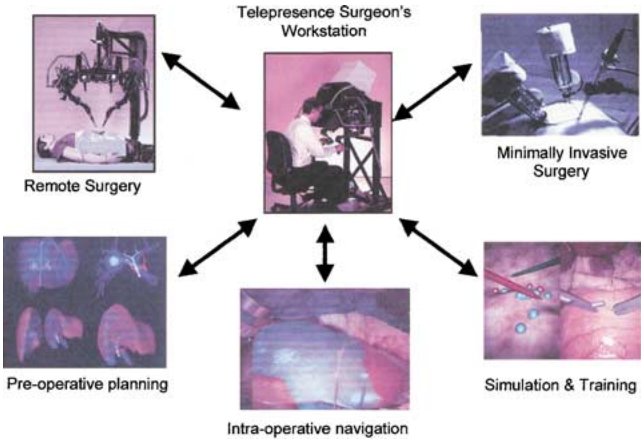

Fig. 1. Concept of total surgical system integration. (Modified by author. Initial diagram courtesy of Joel Jensen, SRI International, 1997.)

Given these available technologies in other disciplines and the emergence of robotic surgery, what is a realistic goal for the operating room of the future? First, the concept must be based on the Information Age. Therefore, the operating room is an information system, and all the components within it are subsystems. They all communicate with each other and share information. This integrated system can be controlled by a single person, the surgeon. The following description is one plausible scenario based on the aforementioned technologies.

The patient is brought to the preoperative suite on an intelligent operating room table (an optimized LSTAT), which is monitoring vital signs. The patient then is anesthetized and connected to the automatic devices (e.g., ventilator, intravenous fluid, drug). The operating room table then passes through a scanner to get a total body scan and moves into the sterile portion of the operating room with no people. While waiting for the patient to enter the room, the surgeon can rehearse the procedure on the scan that was just taken. The operating room table “docks” with the robot, instantly sharing all the information about the patient, thus providing automatic registration for image-guided surgery. The anesthesia is controlled remotely. The surgeon controls the robot, which has additional arms to hold retractors as well as the camera. When a new instrument is needed, the automatic tool changer (not the scrub nurse) changes the instrument, and when a sponge or suture is needed, the automatic inventory dispenser (not the circulation nurse) provides the needed article. As soon as an instrument or supply is used, the patient is automatically billed, a requisition is sent to restock the room, and an inventory request is sent to the supply room to reorder new supplies for inventory. While the surgeon is operating, his or her hand motions are continuously recorded for maintenance of privileges. After using the system many times, the robot remembers the procedure and can provide decision support or prompts when the surgeon deviates from his or her own usual behavior. This results in automatic error detection, improved patient safety, and objective outcomes-based quality assurance.

Such a scenario could be played out in the near future. There are some technical challenges but no barriers. The most important issues will concern the behavioral and social aspects of surgery. Nurses will be very difficult to convince. However, it should be made clear to them that because automatic tool changers and inventory dispensers free them from very simplistic tasks (handing instruments and supplies), they can be promoted to perform supervisory jobs that are more intellectually satisfying and more in accordance with their years of training. There will always be those who raise the legal issues about what happens if the robot is out of control. However, there are as yet no reported incidents, and the systems have built-in redundancy and automatic shutdown. The moral and ethical issues also will be raised, and these concerns should be addressed in a proactive manner.

A powerful argument will be raised by administrators regarding investment in these expensive systems. Because operating rooms are paired around a common scrub and inventory room, there are two scrub nurses, two circulation nurses, one supervisory nurse, and one nurse to give breaks (robots do not require coffee breaks), for a total of six nurses per room pair. The aforementioned scenario can replace five of the six nurses, thereby saving approximately 85% of the personnel cost. Because personnel costs for a suite of operating rooms represent 61% of the total cost, such a decrease in personnel costs, especially with the critical nursing shortage, can be a substantial benefit to the hospital.

This scenario represents what is possible in the immediate future with technologies that are mature and available, needing development and commercialization rather than a scientific breakthrough. A number of technologies in the laboratories can be "wild card," technologies so revolutionary as to change the direction of progress totally, in essence, a disruptive technology. Many of these technologies are considered mere fantasy, yet only 5 years ago, human cloning was considered impossible. Then the cloning of Dolly, the sheep, radically altered the landscape, so that three women currently are pregnant with human clones. Thus the rate of change is much more accelerated than ever, so technology scouting and technology harvesting of speculative technologies has become a scientifically responsible pursuit rather than fanciful daydreaming. The following sections describe some emerging technologies that could make the projected operating room of the future much different from the one described earlier. These technologies are described briefly because in-depth analysis will be presented in subsequent reviews.

Suspended animation

Initial basic research by Safar et al. [1] has resulted in a reproducible animal model with mild hypothermia, in which the animal (dog) is rendered asystolic and perfused with an aortic flush solution that effectively halts cellular metabolism. After 20 min, the animal is rewarmed, and the cardiac rhythm is restored. The animals in this study have no neurologic deficit and appear to behave normally on the basis of quantitative parameters. The principle is that of "controlled cellular metabolism," in which direct manipulation of cellular processes responsible for energy production, enzymatic reactions, and the like, results in the metabolic process being shut down and then reversed. New-generation solutions to lengthen the time of asystole are being investigated. Thus, instead of inducing anesthesia, the anesthesiologist will place a patient in state of suspended animation in the preoperative holding area. The patient will be monitored by the smart operating room table, and no anesthesiologist will need be present. Furthermore, an asystolic patient, theoretically, will experience little to no intraoperative bleeding.

The accomplishment of clinical implementation likely will require at least decade, yet the implications beyond simple "next-generation anesthesia" are significant.

Energy-directed therapy

Dividing, removing, and destroying tissue has been performed traditionally with steel (scalpel), fire (cautery), or simple compression. The latter half of the 20th century saw the introduction of newer methods for tissue therapy that directly applied a number of energies such as radiofrequency, thermal energy, and ultrasound, to name a few. The next generation is beginning to emerge in the form of high-intensity focused ultrasound (HIFU), brachytherapy, and other innovations that accomplish the therapy with minimal or noninvasive techniques, frequently without actually touching the tissue. The difference with these new technologies is that they are image-guided in real time. Unlike, radiation therapy, which exposes a large area to the radiation dose, these new modalities have the precision of a scalpel and even beyond. In addition, research has demonstrated cessation of exsanguinating hemorrhage in a transected aorta in a rat (diameter, 7 mm) by transcutaneous application of HIFU [6]. Surgeons must consider training in noninvasive energy-directed technologies or lose these modalities to the interventional radiologist and others.

Tissue engineering

Current success in growing artificial tissue and organs is limited to planar surfaces such as skin, blood vessels, and cardiac valves because cellular metabolism (oxygen, nutrients, medications, and expulsion of toxins) can be accomplished only by diffusion methods for tissue two to three cell layers thick. Thick solid organs require an extensive vascular and microvascular system. More than a decade of iterative research has resulted in bioartificial vascular scaffolding with vascular endothelial cells that is able to perfuse blood through a microvascular network of 10 μm microvessels. Present research is validating the diffusion capabilities of this scaffolding. The next step will be seeding of the scaffolding with appropriate nephrocyte, hepatocyte, or splenocyte stem cells in a bioreactor to "grow" an artifical organ with the patient's own cells. The implications are that the problems of rejection and insufficient transplant organs will be solved. However, just as significant is the potential to reduce surgery from the vast repertoire of current procedures to a single operation per organ system designed to remove the diseased or injured organ and replace it with a patient's own "newly grown" organ. This is the process used in all other industries. If your automobile has a broken distributor, it is replaced, not repaired. Thus tissue engineering can negate the need for a transplantation specialist, and every surgeon will be a superexpert in replacing an organ.

Regenerative medicine

Unlike tissue engineering, regenerative medicine is focused on applying factors (biochemical, hormonal, genetic, stem cell) *in situ* to cause the body to regrow a specific organ or tissue. The mode of delivery can be intravascular, transdermal, percutaneous, minimally invasive, or even open. The research is in its earliest phases, with some successes in delivery of neuronal or embryonal stem cells to aid in Parkinson's disease [3]. There is also the promise of tissue directed genetic engineering to cause regeneration. This research is so early that it will be decades before clinical trials are undertaken unless a disruptive breakthrough occurs. The surgeon may still have a role in regenerative medicine by providing the delivery of the therapeutic modality precisely to the point of need.

Intelligent prostheses

For nearly 50 years, there have been implantable prostheses (eg., hips, knees, pacemakers, shunts). However, these all have been passive or "dumb." Cardiac pacemakers and defibrillators are the beginning of a new breed of "intelligent" prostheses. These are implanted devices that contain sensors and effectors, with the sensor monitoring the immediate environment and either transmitting the information for a physician to evaluate or responding automatically with a built-in feed-back loop. The MicroMed glucose system [10] is one such system for diabetics, providing a continuous glucose sensor that automatically releases an appropriate amount of insulin from a well when hyperglycemia is detected. A number of orthopedic prostheses are being designed with an embedded sensor to detect strain, torque, and other parameters [2]. Most impressive is the report of the research team of Donaghue at Brown University [11] describing a neural implant in a monkey with which a robotic arm was controlled directly by the "thoughts" of the animal. This raises the question whether there is a significant value to embedding sensors in all organs to monitor and perhaps directly control them.

These latter "wild card" technologies are introduced because the time frame for their development is within the next one to three decades, which is within the professional career of more than half of today's surgeons, and they certainly will become an issue for today's residents. Each of these technologies is so radical that, should they be developed, they will dramatically influence the design and function of the operating room of the future. Instead of being dismissed as mere speculation, these technologies should be monitored closely and subjected to rigid scientific evaluation as they develop. They should be considered now as a serious "spoiler" to a large investment in a new operating room or an entire operating room suite. Basing decisions for the next operating room on current technologies likely will result in an investment that is obsolete in the near future.

The simple fact is that surgeons, nurses, and other surgical health care professionals have not been willing totally to reevaluate their workplace: the operating room. They are comfortable with the current status, and although there is the desire to improve, there is enormous resistance to change. It is unlikely that the operating room of the future will precisely match the preceding description. However, the concept of systems integration to reduce error and improve patient safety, along with a long-term substantial reduction in costs, makes such a concept worth subjecting to a stringent scientific evaluation. Strategic planning must consider the emerging technologies, and take appropriate steps in design that will provide flexibility and militate against obsolescence as much as possible. When performed in other industries, the benefits of this approach have been unequivocally clear.

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