# How the Future of Surgery is Changing:

# Robotics, telesurgery, surgical simulators and other advanced technologies:

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# How the Future of Surgery is Changing: Robotics, telesurgery, surgical simulators and other advanced technologies

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***Abstract:*** *Since the advent of minimally invasive surgery, there have been new discoveries in robotics to perform telesurgery, in virtual reality and surgical simulators for surgical education and many emerging new technologies to revolutionize what the future of surgery will become. This is a review of the state of the art in these related fields, of disruptive technologies in the laboratories and the long term implications of the radical new technologies that are emerging.*

## Introduction

Although many factors, such as economics, managed care and regulation contribute to the changing landscape in surgery, nothing causes such dramatic change as the introduction of a revolutionary technology. The change is so rapid in fact, that a new term, disruptive technology, is applied to signify such abrupt and radical change in a short time. The American baseball coach, Yogi Berra very cleverly anticipated such change when he said “The Future is not what it used to be!”. The implication of course, is that we cannot judge future changes by using contemporary standards. Laparoscopic surgery was the first of such technologies, and many others are soon to follow. Robotics is just emerging onto the scene, along with virtual reality for surgical simulation – and many others are in the laboratory today. The following is a review of the current status of robotics, telesurgery and surgical simulators as well as an introduction to numerous other new technologies that may significantly impact upon the practice of surgery. The rapid rate of such technological change is creating such extraordinary social, behavioral and ethical upheaval that speculation upon their profound effects is warranted.

## Surgery in the Information Age.

Before examining specific technologies, it is important to provide the framework for a change of such magnitude. This radical change is a reflection of Information Age technologies, such as computers, robots and virtual reality. However there are some underlying principles that must be understood, since it is this “Information Age perspective” which not only drives the change, but binds everything together.

The first principle is that we can represent real objects in the real world with a computer or information equivalent (this is Nicholas Negroponte’s ‘Bits instead of atoms’ analogy[1]) – for example, your body in the real world and a CT scan of your body in the information world. To this total body image is added all the vital signs, mechanics, physiology, etc of an individual person. The result is an information representation, a holographic medical electronic representation (or holomer) [2], of a person which is a surrogate for the patient or person in information ‘space’ (computer), and which permits simulation upon the image before actually providing medical diagnosis or treatment on the person (see below). The US military has a proof of concept project called the Virtual Soldier, in which a total body computer tomography (CT) scan of a soldier is used to represent the soldier (Fig 2). By carrying this scan on the electronic dog tag, if the soldier is wounded, the medic or surgeon will have an image of what the soldier was like when he was well. A comparison to the soldier after wounding allows the surgeon to diagnose what changes occurred – however in the absence of a surgeon, a medic can use a computer program to automatically detect the difference and perform the diagnosis for the medic. This is such a daunting project that it is only in its initial phases, creating a holomer of a heart, that behaves completely like a natural heart.

There is much debate about the value of a 'total body scan' (holomer) of a person, ranging from the theoretical increase risk of cancer due to radiation exposure to the practical problem of the expense of performing many more tests and examinations if some abnormality is discovered. However, these arguments miss the main point – the purpose of obtaining a scan is *not* to discover disease, rather it is best employed when the patient is younger and asymptomatic in order to provide a baseline (in scientific terms, a 'control when normal'). Thus when a person becomes sick, there will be an available dataset (image) of their normal healthy state for comparison. Clinical medicine frequently pretends to be scientific – true science requires rigid adherence to the scientific method. The basic premise is the there is a control, by which to compare a change – however without a holomer we do not have the control arm and therefore are not always truly performing evidence based medicine.

Evidence-based medicine is an important advance for scientifically applied medicine, and one important outcome measure to confirm our diagnoses in patients who have died is the autopsy. For numerous reasons, the number of autopsies are drastically decreasing, with less that 10% of all hospital deaths being confirmed by autopsy[3]. Thali, et al had introduced a new technologic concept, the virtual autopsy, which is a total body scan of the deceased[4.] An additional project by the military, Virtual Autopsy (Fig 3-5) performs total body scans after a soldier is killed in action and is used in assisting the pathologist during the real autopsy. Having the image from the Virtual Autopsy available has reduced the time for the autopsy by 30% and increased the recovery of forensic evidence (metal fragments) from 60% to 85%[5]. But more important, with the image it is possible to calculate and infer many important facts from the wound tract, fragment position, etc that is not possible from the real autopsy. Now information such as what areas of the body were protected by armor, how should armor be redesigned, which direction the bullets came from, what was the velocity of the bullets, and how far away was the enemy can all be derived by analyzing the image. Interestingly, such type of analysis has been commonplace for decades in all other industries except healthcare. Scientists and engineers all have a computer (or information) representation of their product (in healthcare the 'product' is the patient). Therefore it is possible to do modeling, simulation, virtual prototyping, virtual testing and evaluation, mechanical rehearsal, and many other techniques on the computer model before even building or running their product. Healthcare could have such an opportunity if a total body scan were taken of the patient.

**Robotics and telesurgery**

Another important aspect of the Information Age is to look at our devices and instruments as 'information representations' (Fig 6). For example a robot is not a machine, it is an information system with arms or legs; a CT scanner is not a digital imaging system, it is an information system with eyes, and so on[6]. The importance is now nearly everything we do as surgeons can be considered as 'information'. A specific example is robotic surgery. Laparoscopic surgery is half way to becoming robotic surgery – we do not look at the persons organs (real world), but look at a video monitor, which is a computer (or information) representation of the organs; however in laparoscopy, we manipulate the tissues with real instruments. In contrast, a robot also uses a video monitor (information) but when the surgeon moves the handles, electric signals (information) goes through the computer to the instrument tips. Surgery has become a form of information management.

This is an extremely important concept, because using this perspective, it is possible to integrate surgery as never before. From the robotic surgical console (Fig 7), the surgeon can perform open surgery, minimally invasive surgery and even remote (tele) surgery. By importing the CT scan of the patient (or organ), the surgeon can pre-plan the operation and even do a surgical rehearsal of the procedure, safely making mistakes upon the image rather than the patient. By performing data fusion of the CT scan to the real video image, it is possible to have intra-operative navigational aid for image-guided surgery, and by using a computer generated virtual reality image of organs, surgical simulation for training and assessment can be performed. All these different aspects of surgery, which currently are performed at different times in different places, can now be done together from one spot – the surgical console. This allows the integration of surgery at a level not previously possible. It is this integration – a systems approach – that is the real power of robotic surgery.

The mechanical advantages of robotic surgery have been often been enumerated – increased precision of hand motion, removing tremor from hand motion, magnified view, improved dexterity and remote surgery. The first telesurgery operation was performed by Professor Jacques Marescaux of Strasburg, France in September, 2001 (Fig 8) [7], and Dr Mehran Anvari[8] of McMaster University in Hamilton, Ontario Canada is performing advanced robotic surgery to North Bay, Canada approximately 300 km distant. While it is possible to accomplish such surgery, it is not always feasible or practical, such as in major cities where there are ample hospitals with specialists available.

**Future surgical ‘instruments’**

Most surgical instruments are mechanical, although a few such as electrocoagulation, radiofrequency ablation, cryotherapy are available. This shows one new trend, which is to replace mechanical instruments with energy systems. An innovative new example is using ultrasound. Currently available is the Sonosite 180 diagnostic ultrasound system (Fig 9). Research is being conducted to add to the system, high intensity focused ultrasound (HIFU). When two identical ultrasound beams are focused to intersect each other, harmonic inter action occurs, which generates heat. Depending upon the frequency, power, etc, the heat can be generated to either coagulate tissue and blood or even to vaporize tissue. Clinical trials are being conducted in areas such as uterine fibroids, prostate cancer, benign breast lesions, and liver lesions. By combining HIFU on the diagnostic ultrasound (as in Fig 9), it will be possible to use the Doppler to diagnose a source of bleeding, focus the HIFU, and stop the bleeding – all from outside the body. Animal research has been successful in non-operatively stopping hemorrhage from femoral arteries (pictured in Fig 9) and solid organs like liver, kidney and spleen[9]. It is likely that more and more energy directed instruments, such as lasers, radio frequency, cryotherapy, ultrasound, etc will be emerging which have both diagnostic and therapeutic possibilities, permitting the surgeon to make a diagnosis and then perform treatment simultaneously. Another instrument, called the “smart scalpel”, is in research with the military to create a laser scalpel which scans the tissues in front of the cutting laser to diagnose if there are blood vessels in the area, and if so, the laser is automatically shut off so as to not cut through major blood vessels. Next generation will attempt to distinguish normal from cancerous tissue to aid in oncologic surgery.

**Trauma and surgical critical care**

For decades, the military has been using a new system called the Life Support for Trauma and Transport (LSTAT) (Fig 10) which has all the capabilities of an intensive care room reduced to a 6 inch platform that sits below a standard stretcher[10]. In addition, there is full telemedicine capabilities. Ever since 2000 in the Bosnia and Kosovo war, the military has been using the LSTAT for casualties. Figure 11 represents such a typical scenario: A wounded soldier is placed on the LSTAT immediately after wounding and the surgeon at the MASH receives information about the casualty. From the helicopter, to the ambulance at the helipad to the emergency room triage, the surgeon keeps monitoring the casualty, changing the respirator, IV fluids, etc as necessary. The patient is transported to the OR and after surgery to the recovery room on the LSTAT, all the while the surgeon is monitoring him and a complete record is being kept. During the entire episode, the surgeon has been completely informed and is completely in charge, which is yet another form of total integration of surgical care through information management. The next generation LSTATs (Fig 12) will be lighter weight, hot-swappable components and with even a portable backpack version.

In the military trauma care, rapid medical evacuation has been an important contribution to the improvement in survival of casualties from the battlefield. There is a new emphasis in the military on unmanned air vehicles (UAV), and the latest effort will be to replace trucks and other supply-chain vehicles with a new corps of resupply UAVs. The vast majority of medical evacuation occurs on 'vehicles of opportunity", such as High-Mobility Multipurpose Wheeled Vehicle (HMMWV) and 2 ½ ton trucks. With the new resupply UAVs (Fig 13) soon to be distributed ubiquitously throughout the battlefield, it is highly likely that the majority of the medical evacuation will eventually occur on a UAV, so next generation resupply UAVs are being designed to incorporate LSTAT platforms, in essence converting any empty UAVs into a fully capable autonomous medevac vehicle (Fig 14).

**Education and training**

Training in surgical skills and surgical certification has not changed much in centuries (fig 15). However recently, aviation simulation technologies, which first begun in the 1950s (fig 16) and have become ultra-realistic (fig 17), have transitioned to surgery made their first appearances in the 1990s in surgical simulation (fig 18) [11]. Using virtual reality (fig 19) and the exponential growth of computers, progress has been rapid to a point where surgical simulation is becoming very realistic and even portable (fig 20). Modern adult learning principles combined with new methodologies (fig 21) of objective assessment have brought simulation for surgical skills into the 21$^{st}$ century. Sophisticated systems, such as the red dragon and blue dragon (fig 22) provide accurate measurements of hand motions, forces, direction etc. This results in a quantifiable 'signature' of skills assessment which accurately distinguishes the performance of a novice from an expert and which provides quantifiable information on how to improve performance (fig 23) [12]. With the ability to so accurately quantify performance, the next generation simulators will be incorporating the performance of experts as the benchmark criteria which students much achieve. Training programs are now changing from chronology (time) based training to proficiency-(criterion-)based training; the student no longer trains for a given time and then begins operating, instead the student continues training on the simulator until they achieve the benchmark 'criteria' of an expert before they operate upon their first patient. This dramatically decreases the amount of time a student will 'practice' on a patient. The Yale University study demonstrated that criterion-based training on a simulator can decrease operating time by 30% and decrease errors by 85%[13].

**Surgery without incisions**

The progress from open to minimally invasive surgery has dramatically improved patient recovery and outcomes, greatly due to the reduction of incisions from very large to extremely tiny. There is current research in eliminating incisions entirely by inserting instruments through natural orifices (natural orifice trans-luminal endoscopic surgery – NOTES), such as mouth, vagina, anus, etc[14]. This requires the modification of current flexible endoscopic instruments (fig 24). The most common is trans-gastric, where a flexible endoscope is inserted into the stomach, and an incision is made in the stomach so the endoscope can be passed into the peritoneal cavity (fig 25). Then the surgical procedure, such as appendectomy, cholecystectomy, etc is performed somewhat like laparoscopy, but with long flexible instruments. Upon completion, the specimen is retrieved through the stomach and mouth, and the incision in the stomach is closed. New instruments are being designed to improve upon this new approach (fig 26), including innovative suturing devices (fig 27). The most important feature of this new approach will not be the use of natural orifices as much as whether there will be significant improvement for the patient over current laparoscopic procedures – success must be determined by patient outcomes.

Just as in laparoscopy, if the initial success occurs, there is no telling just how much surgery can be accomplished through this route (fig 28).

**The operating room in the future**

With the rapid changes in robotics, computers and virtual reality it is clear that the place where surgical procedures will be performed must change. New technologies require a new approach. Until now, the operating room has been an empty space filled with supplies, furniture (tables, monitors, etc), anesthesia machines, lights, etc. All of this equipment is passive, independent and not inter-operable. The next step is the integration of all aspects of the operating room, not only for the surgical procedure, but during the entire peri-operative period, from the moment the patient enters the pre-operative holding area until finally discharged from the recovery area. As much as anything, it is an integration of the information about the patient, procedure, processes, work flow, etc. New business principles, such as supply chain management, asset tracking, just in time inventory etc must become standard features in the entire surgical procedure[15]. Access to information, such as laboratory data, images, etc will become available at the surgeon's fingertips and displayed upon the same or adjacent monitors as the surgical procedure. New concepts may emerge from new technologies, such as the 'operating room without lights', in which the ceiling is embedded with a thousand light emitting diodes (LED) in the ceiling to replace the conventional overhead spotlight, permitting complete lighting of the operating room without obstructing beams[16]. Perhaps hundreds of miniature inexpensive cameras will also be embedded in the ceiling, allowing for recording, tracking, work flow management, etc (fig 29). In essence, the ceiling will become an 'intelligent sea of cameras and lights' and actually participate actively in the procedure, rather than simply creating a passive space.

It is important to also look toward industry for inspiration as to the potential direction for surgery, especially the new technologies including robotics. Today, surgeons sit at robotic work stations, but scrub nurses change instruments and circulating nurses bring supplies. However in industry, when an instrument is changed, an automatic tool changer is used, or a new supply is needed, a supply dispenser is used – there are no people interacting with the robots. Michael Treat of Columbia University[17] has designed a robotic scrub nurse (fig 30) with responds appropriately to verbal requests, handing the needed instrument to the surgeon and picking up and returning the used instrument to the surgical tray. This is a stepping stone to a completely automated operating room – the operating room without people. The following is a suggested concept, which the military is funding initial research.

The patient is brought to the holding area, placed in the proper position for surgery and anesthetized. A total body scan is performed (fig 31) and while the patient is taken to the operating room, the surgeon rehearses the surgical procedure on the work station, making errors on the patient's image and not the patient. When the patient is being operated upon, every time an instrument is changed or a supply is used, three things happen: The patient is billed, a request is sent to resupply the operating room and an order is sent for a new replacement – all within 50 milliseconds with 99.99% accuracy, which is current industry standard. Such a scenario has significant benefits, especially in efficiency and personnel reduction. Replacing a scrub nurse and circulating nurse during the procedure would decrease costs, free the nurses for more important peri-operative patient tasks than the simple pick-and-place of handling instruments and supplies, standardize accountability through automatic instrument and supply tracking and many other work flow improvements. However, is such a scenario pointing to a future where robots replace surgeons? This is not likely, although once again looking toward aviation and the military, there are analogies. Until the year 2002 fighter pilots, like surgeons, were the peak of performance. Then came the UAVs, such as the Predator (fig 32). Initially it was used for surveillance, then for hunter-seeker missions, and now for full combat. The military is fully committed to replacing all fighter aircraft with

UAVs by the year 2025, and there is even a new Air Force school for Remote Pilot Training (pilots that never get into an aircraft but remotely control a UAV) – is there a lesson here for surgeons?

**Mobile Robots**

In addition to the current operating room robots, a number of mobile robots are being introduced. The RP-6 mobile tele-medicine robot from In-Touch, Inc of Goleta CA (fig 33) is a robotic platform with a flat-panel monitor supported by a telemedicine connection[18]. The nurse can go with the robot on rounds, and the patient can see and converse with the doctor over the telemedicine link. There has been surprisingly good acceptance of this technology, especially in nursing homes where physicians do not have much time for rounds. When interviewed, the patients state that they quickly become accustomed to seeing their doctor on the video monitor, and frequently prefer this method of communication because the surgeon takes more time and has better eye contact with the patient – a rather surprising result of the survey. Or perhaps it is a sad commentary upon how busy surgeons must practice today, speeding through rounds and giving up the all too critical value of personal attention to the patient.

**Advanced technologies beyond current practice**

The technologies described above are those at the leading edge today. However there are a number of disruptive technologies[19] that are changing fundamentally the way medicine and surgery will be practiced. The disruption go so deep as to change the very basis of how science is being conducted[20] The scientific method is the hallmark of good science, and is characterized by development of a hypothesis, conducting the study design, performing the experiment, analyzing the results and reporting the outcomes. What has been occurring is that an intermediary step is being performed, after the study is designed. This is to develop a model on a computer and simulate the experiment, then the actual experiment is performed. It has been the rise of the computer that has given the sophisticated models, such as automobile engines, airplanes, etc from computer aided design/computer aided manufacturing (CAD/CAM) software, which then is taken through numerous simulations using virtual prototyping, virtual testing and evaluation to simulate the best potential outcome. Then only the most likely successful products will be produced and tested. This methodology – modeling and simulation – has dramatically reduced costs, time and errors to develop a new product or test a new method or procedure. In the example above of the holomer, it will be possible in the future to acquire de-identified data about millions of patients. Then it might be possible to conduct an experiment upon a million patients (holomers) for fifty years in one weekend – on a supercomputer. Large scale (high dimensional) simulation is what is done in other industries, such as weather forecasting, drilling for oil, constructing and testing models for a new plane or auto, etc. In short, the scientific method has actually begun the transformation by adding the additional step of modeling and simulation to the scientific discovery process (fig 34). The message is clear; modeling and simulation are at the heart of the transformation in the Information Age, and healthcare must begin implementing these technologies where ever possible, such as surgical education, pre-operative planning, and surgical rehearsal.

However it is apparent that this new methodology which defines the Information Age is already present, and there is consensus that we are in the Information Age. Therefore, the Information Age is *not* the future – it is not possible to be the present and the future at the same time. So something else must be the future. A glimpse of what the future might become was given by Alvin Toffler in his 1976 book "The Third Wave" [21], in which he described the three different 'ages' – the Agriculture Age, the Industrial Age, and the Information Age. There appears to be a new age emerging – tentatively called the BioIntelligence Age until a better name is coined[22]. In figure 35 is a curve of the emergence of the ages, noticing that there has been a long 'tail' at the beginning when early discovery (or laboratory research) occurs. The slope rapidly increases during the revolutionary phase, as the discovery(ies) are introduced, and as businesses take advantage to commercialize the new products. There eventually comes a time when the discovery(ies) are accepted by everyone as commonplace (consumer acceptance), and at that time there are no new discoveries; instead there is evolutionary progress where the existing products are refined and new features are added, but the basic discovery is unchanged. The Information Age has reached this tipping point from revolution to evolution. Over the past 20 years there have been no new discoveries, the cell phone, computer, etc are fundamentally the same as they were 20-30 years ago, the only difference is that they are more sophisticated or have more features like small size, built in cameras, internet access, etc; these products perform exactly the same functions as they had in the past, or combine existing functions into a smaller package.

In discussing possible new directions for the future, a few factors stand out. The most important characteristic is that the BioIntelligence Age is that of a multi-disciplinary approach (fig 36). Until now, research, products, etc were typically a result of work in one of the three main scientific areas: Biology (Life Sciences), Physical Sciences (including Engineering), or Information Sciences. However new discoveries are occurring at the intersection of these disciplines. Is the Human Genome a result of biology or information science – it is both because DNA is a living information system. The same can be said of new biosensors (biology and engineering) or intelligent robots (engineering and information). Thus, the future is that of multi-disciplinary approach, whether in research or even in patient care (many different specialties are frequently involved in the care of a patient). It is clear that it is now possible to understand our world (and patients) at a whole new level of complexity, however no single person or physician can understand even a small part of the whole. Thus the need to form interdisciplinary teams and practices in order to make revolutionary progress. Exactly what are these new technologies that will so revolutionize healthcare (fig 37)? The following are a few examples.

**Fusing of living and non-living systems (man and machine)**

In 1999 Eric Staudacher at University of Michigan placed a miniaturized sensor and radio transmitter onto bumble bees (fig 38). The sensor was sensitive to simulated anthrax. The military then conducted trials where soldiers were given the bees; the simulated anthrax was released, and the soldiers released the bees, which then flew out into the area; and when the anthrax was encountered, the sensors radioed the information back to the soldiers to avoid that area. This combined system –bee and sensor – performed something that neither system could do alone. At the laboratory of Robert Fuller of University of California, Berkeley there are experiments with cockroaches with probes implanted into their brain[23] (fig 39). The cockroaches are then put on a treadmill to record their brain waves while they are running on a treadmill – with the purpose to build a better robot by deciphering how the cockroach moves – it is nature's most efficient motion machine. One evening the students went back to the laboratory and reversed engineered the system by disconnecting the wire that records the signals and connected the wire to a joystick to send the signals. After a short time they were able to drive the cockroach around the laboratory with a joystick. The usefulness of such as project is not clear, but imagine if a miniature camera (like those in a cell phone) were put on the cockroach as well, it might be possible to use them for disasters (earthquake, tsunami, etc) because they can search where even dogs cannot go. Today, the military is using mobile robots on the battlefield to search for ambushes in caves, homes and other dangerous places.

**Miniature robots**

Miniaturization using micro-electronic machine systems (MEMS) has been explored for over two decades. It has allowed scientist to create systems on the mesoscopic scale (millimeter scale). New robots have become extremely small with entire computers, sensor systems and locomotion incorporated into a robot the size of a small coin (fig 40). The first clinical miniaturized 'robot' was the videoendoscopic capsule by Paul Swain[24]. This is a pill size capsule inside of which is a miniature camera, light source and transmitter. The patient wears a video recorder on their belt. After swallowing, the capsule transmits images (one frame every 30 seconds) as it passively goes through the GI tract. The next generation is being researched to be able to control the direction and passage of the capsule (robotic control) and eventually add small end effectors such as biopsy forceps in order to perform therapeutic maneuvers.

**Cellular Surgery (Biosurgery)**

Beyond mesoscopic scale is the microscopic scale and individual cells. A new technology, called femto-second lasers (or ultra-short pulsed lasers) emit pulsed laser light at $1x10^{-15}$ sec (fig 41). When directed at a cell membrane, it is possible to create a hole (incision) into the membrane without damage, providing access into the cell[25]. Various researchers are beginning to manipulate the individual structures within the cell; and a group in Dundee, Scotland is actually entering the nucleus and manipulating chromosomes. One might speculate that in the future, surgeons will be using such systems to actually manipulate individual genetic material or perhaps directly operate upon genes. If this were to occur, the results of surgery would be to change the very biology of the cell (biosurgery), rather than trying to remove organs or restructure tissues[26]. Such research is now conducted by controlling the position of the laser from a workstation (fig 42). Interestingly, this is very similar to what surgeons are doing today with robotic surgery, the main difference is that the scale in cellular surgery is thousands of times smaller (fig 43). In addition, the researchers are using other tools, such as atomic force microscope (AFM), to manipulate and visualize cells. These video monitors for the AFM show not only the outlines of the cells, but the actual forces between cells (fig 44), giving researchers a whole new way of 'seeing' the function of a cell.

**Robotic controls**

Many of the systems described above are robotic systems that are controlled from a typical work station similar to the DaVinci surgical console. However as smaller and more complex scales are explored, there may be a need for a different method to control these systems. Numerous universities are working on direct neural control, the so called brain-machine interface. A probe (fig 45) is inserted into the brain of a monkey. These probes have multiple tines, so hundreds of individual neurons can be sensed. The experiment is conducted as follows (fig 46) [27,28]: A probe is inserted onto the motor cortex of a monkey, connected to a computer to analyze the EEG signals, and the monkey is taught to use a joystick to move a green dot on a computer monitor to cover a red dot. When the dots merge, a robotic arm feeds the monkey. The EEG is monitored and the researchers interpret the motion signals. Once the signals are interpreted, the wire from the brain probe is disconnected from the computer and connected directly from the brain to the robotic arm (similar to the cockroach experiment). It takes about 6 weeks for the monkeys to realize that they do not have to move their arm or joystick to feed themselves. There are now 5 universities with monkeys that feed themselves simply by thinking (fig 47) – thoughts into action. The first clinical trials on a quadriplegic man began in 2005, and after 3 months this person was controlling the cursor on a video monitor, turning the television on and off, and even opening and closing the fingers of a prosthetic arm – simply by thinking. At the University of Hawaii, research is being conducted to pick up the EEG signals through the skull without implanting probes into the brain (fig 49); there has been only modest success to date but there is continued progress. Is it possible that in the future a surgeon could place a cap upon their head to control a robotic system?

**Intelligent Prostheses**

There has been significant progress in developing intelligent implantable devices. The initial implantable cardiac pacemaker, which began over 50 years ago as a simple pulse generator to stimulate the heart for complete heart block, has now become an extraordinarily sophisticated monitoring, pacing and even automatic defibrillation system. Prosthetic lower extremities for above knee amputation now include sensors, actuators and feedback control loops[28,30](fig 50)so that amputees are now returning to nearly perfectly normal gate. Some amputees have special prostheses for sports, mountain climbing, etc that actually exceed the performance of a human leg. There are now a number of soldiers who suffered severe injury resulting in amputation that have returned to full combat duty. Other prostheses, such as artificial retina (fig 51) and artificial cochlea are still very crude but are beginning to restore a modest amount of sight and hearing. The progress in biocompatible materials, MEMS miniaturization, intelligent feedback control and other technologies are making it possible to replace more and more lost tissues or organs with prostheses.

**Tissue Engineering**

There are numerous approaches to replacement with synthetically grown tissues or organs, using the science of tissue engineering (fig 53). This is the epitome of multidisciplinary medicine. An example is Dr. Jay Vacanti or Massachusetts Institute of Technology and the Massachusetts General Hospital in Boston in creating an artificial liver[31]. Computational mathematicians designed a microvascular pattern with a vascular branching pattern to a 10 micron level. This pattern was exported to engineers with a stereolithography machine that 'printed' out 3-dimensional vascular structure using bioresorbable substrate from biologists that was embedded with vascular endothelial growth factor, platelet derived growth factor, angiogenesis factor and others from molecular biologists . This bioresorbable scaffold was then placed in a bioreactor with vascular endothelial cells; after about 2 weeks there was a living vascular system. This system was then perfused with blood, and placed in another bioreactor with hepatic stem cells, and the result was a small sample of a living portion of liver. The next steps are to take this for implantation into animals. With simpler organs, Anthony Atala of Wake Forest Medical Center has used scaffolding to grow an artificial bladder – he has reported his 5 year follow up in patients, all of whom have had successful implantation, and most have even reestablished neuronal control of bladder function[32].

**Genetic Engineering**

There are many examples of genetic engineering , however there is one aspect that is particularly significant, and that is transgenic genetic engineering – taking genes from one species and inserting them into another species. The orb spider produces the strongest known naturally occurring fiber in its silk. Nexia Technologies of Montreal, Canada has taken the genes for the production of this protein in the spider and inserted it into goats (fig 54); now there are herds of goats which are producing the protein in their milk, from which the silk fibers can be reconstructed from the protein[33]. This is but one example of taking genes from one species to the next. Perhaps in the future, rather than bricks, mortar and smokestacks, there will be herds of animals or fields of plants producing things that we need, including the surgical sutures that we use..

**Hibernation and suspended animation**

A remarkable discovery was made by Brian Barnes of University of Alaska, Fairbanks – animals do not hibernate because it is cold, they hibernate because the can 'turn themselves off'[334] (fig 55). Actually, the Artic ground squirrels put themselves into a hypometabolic state, with vital signs that are radically reduced to a few percentage of normal (fig 56). This occurs because some molecule in the hypothalamus is secreted – if the area in the hypothalamus is ablated and the ground squirrel is placed in the cold, it will freeze instead of hibernate. Also, if you put a normal ground squirrel in the desert surrounded with food, it still will hibernate. The signaling molecule from the hypothalamus is unknown, but it has been discovered that on the mitochondria where energy (ATP) is produced, a molecule blocks this site and oxygen cannot transfer its electrons to ATP to create energy. Mark Roth of Fred Hutchinson Cancer Center in Seattle has experimented in mice and been able to create such a block in mice such that they are put into a state of suspended animation for about 6 hours[35] – no respiration, heart rate, blood pressure, EKG, EEG, body temperature assumes ambient temperature and even no activitiy on functional

MRI of the brain. After 6 hours they are awakened and they behave normally, remembering which button to push to feed themselves and learning new pathways in a maze. While this is an early experiment in a very long research effort, it points to the possibility of using these molecules or drugs for anesthesia. If successful, in surgery a patient could be put to 'sleep' with no heartbeat, no bleeding when incised (bloodless surgery), not able to feel pain, unable to move, etc and when surgery is over, can be awakened.

**Moral and Ethical Considerations**

We are in an era of truly 'outrageous' science (outrageous – *aut-'rA-j&s* - Exceeding established or reasonable limits; daring; provocative; improbable; extraordinary) [36]. The technologies described above certainly exceed any expectations that could have been anticipated as little as 10 years ago, let alone 50 or 100 years ago. However there is a more important issue about these discoveries – they raise moral and ethical questions that are well beyond the promise of any technology in the past. Previous discoveries impacted upon an individual or group of individuals, however these discoveries are impacting on the very foundations of civilization as we know it. The reason is that technology is far outstripping our ability to adapt (fig 58). The acceleration of technology is increasing exponentially, and business is following close behind to exploit the technology. However our social systems cannot respond as quickly, and healthcare systems have an even slower response [37]. Because of the consequences of an untoward effect of a new technology, physicians must very stringently evaluate the technology and they must refrain from 'jumping on every new bandwagon'. Such cold deliberation and assessment requires a very long lead time, so it is imperative to look at the moral and ethical considerations early in the development of a new technology. Physicians must participate in these decisions, or have the implementation and results of the innovation be determined by those with political or selfish motives (fig 59). Technology is neutral – it is neither good or bad; it is our responsibility to breathe a moral and ethical life into the technology and then apply them with empathy and compassion for each patient. The following are some examples of technologies that pose extraordinary ethical challenges.

**Human Cloning**

In April 2002, an announcement was made public that the first human was impregnated with a clone (fig 61), and 9 moths later the first human clone was born. The immediate response from all governments was to ban human cloning, however today there are at least 3 countries that support human cloning (fig 62). The debate continues over human cloning (and stem cells) while science is left with conflicting messages, reduced funding and the threat of suffocating oversight. Who should decide what (or who) should be cloned? Should brainless clones be developed as spare parts? Do we really need to clone more people, what will happen to the human population? We have difficulty in feeding many people today.

**Genetic Engineering**

The first genetically engineered child was born in 2003 (fig 63). There are also a number of children born with the additional goal of harvesting their stem cells to save a sibling ('savior babies'). But even more radical is that of transgenic genetic engineering (similar to the orb spider and goat). Humans have 4 rhodopsins for vision, only using two. The pit viper snake has one of the same rhodopsins that are unused by humans, and which gives the snake the ability to seek its prey in infra-red[38]; the humming bird can see in the ultraviolet[39]. Should we genetically engineer our children to give them such abilities, so they can see in the dark? Should they have abilities that others do not have, giving them an enormous advantage? And who will decide which children can be 'enhanced'? Are we on a threshold of designing our children to a point where there will be a whole class of enhanced individuals?

**Longevity**

There are at least 3 strains of mice which prolong their lifespans by two- or three-fold, using apoptosis, telomerase, nutritional manipulation ,etc[40] (fig 64). Should these same mechanisms be successful in humans, the normal human lifespan would increase to 150-200 years. What are the profound consequences of living that long? Does a person retire at 55-65 years of age, have multiple careers, etc? Without people dying, the population will increase even faster.

**Intelligent robots or computers**

Noel Sharkey, professor of engineering at Sheffield University (Sheffield, UK), has programmed little robots with 'rules based programming' which permits them to learn. He placed them in a room with scattered junk and closed the door. The robots rummaged around over a 6 month period. One day, the door was open and one of the robots escaped – out the door, down the steps out another door and was caught scooting across the parking lot[41] (fig 65). This robot had never seen a stair, door or the outside, but he was able to navigate out of the building. Does this represent a low level of intelligence, perhaps as smart as an ant? Are we finally on the threshold of developing a useful level of intelligence for computers and robots?

Pioneers in robotics and artificial intelligence, such as Hans Morevac[42] or Ray Kurzaweil[43] point out where computers stand in relation to the human brain in terms of computer power (fig 66). Based upon the number of neurons and synapses per neuron, it is roughly estimated that the human brain computes at $4.0 \times 10^{19}$ computations per second (cps). The fastest computer to date is computing at approximately $3.5 \times 10^{16}$ cps – approximately 1000 times slower than the human brain. However, it appears that Moore's Law (roughly translated that computer power doubles approximately every 18 months. Do the math! In approximately 10 doublings, or in 15-20 years, computers will be computing as fast as the human brain. Will the computers be intelligent, and if so, should they be granted 'rights'? Will we be able to recognize their intelligence? Will they remember we made them – or even care? If the computer plug is pulled, will that be murder of an intelligent being? These and many more seeming trivial questions are now taking on serious connotations as the technology moves rapidly forward

**Replacing body parts.**

With the rapid progress in tissue engineering, synthetic organs, intelligent prostheses, regeneration and other technologies, it will soon be possible to replace most any part of the body (except brain) (fig 68). With prostheses becoming so specialized and much superior to a persons own body part, is it ethical to remove a 'normal' leg or eye and replace it with a synthetic one that is much better than the one a person is born with? If a person replaces 95% of their body with artificial parts, are they still human? What exactly is it that constitutes 'human' – the flesh and blood with which a person is born, or is there something more?

**Conclusions**

Technology is advancing so quickly that even as we implement a new procedure such as laparoscopic surgery, new technologies to replace it (such as robotic surgery) are close behind. The new sciences are producing remarkable new opportunities, especially with the emerging non-surgical technologies such as artificial organs, regeneration, prostheses, suspended animation and others. Some of these technologies will increase the surgeon's ability to perform surgery, others will replace the need for surgery. If there is any lesson to be learned, it is that at today's rate of change, every surgeon will see not one, but many revolutions during their career – the practice of surgery is changing faster than any time in the past.

The technologies described above, and the speculation on their possible moral and ethical consequences, should awaken a new awareness of responsibility that we, as surgeons, must accept. Ignoring the possible, no matter how outrageous it may seem at this time, puts future generations in jeopardy. While neither the scenarios as painted nor the moral and ethical issues as postulated will come to pass exactly as described, it is clear that the hard science behind the issues will inexorably continue, and at an alarmingly accelerated pace. What is pure fantasy today will become tomorrow's undisputed fact. But more important, the moral and ethical issues are so profound that it will take decades to find equitable solutions that are both philosophically pure and pragmatically executable. And who better to participate than those who have taken a sacred oath – the Hippocratic Oath – and accepted stewardship for their patients and students. It is mandatory to instill in our students a feeling of urgency, a sense of magnitude and an acceptance of obligation to not only our patients and the profession, but all of human kind. Upon their shoulders quite literally rests the destiny of the humans species. To ignore this burden is to abdicate to those (such as politicians, lawyers, etc) who blur the sacrifice of idealism with their own reality of self interest. To paraphrase Francis Fukyama when he is describing "Our Post Human Future"[44], we are now closing in on the ultimate question: "… Today there walks upon our planet, a species so powerful that it can control its own evolution, at its own time and choosing … *homo sapiens*. What new species shall we choose to become?"

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Illustrations

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