Abstract
In this review, we introduce and describe telesurgery ("surgery at a distance"), a technique which allows surgeons to robotically operate on a patient while being at a considerable distance from the operating table. Telesurgery has been made possible by extraordinary advances in the fields of robotics and telecommunications and has the potential to revolutionize healthcare delivery in the near future. Discussed here are: 1) the various applications of telesurgery (including civilian and military), 2) its advantages over conventional surgery, 3) the robotic systems currently in use and 4) the technical and financial issues associated with this technology. Although telesurgical technologies are still in their early stages of development, their potential use in disseminating advanced healthcare to previously inaccessible settings should be recognized.

Introduction
In an unprecedented feat in February 2001, a team of surgeons performed a laparoscopic cholecystectomy (gallbladder removal) on a woman in Strasbourg, France. The remarkable thing about this rather unremarkable procedure was the fact that the surgeons were operating from a hospital 6000 kilometers across the Atlantic in New York City. The 54 minute operation, aptly named "Operation Lindbergh" in honor of Charles Lindbergh and his breakthrough solo flight across the Atlantic, was completed without any complications and the patient was discharged two days later.

The success of this operation as well as the technological infrastructure set in place highlight major developments in the field of telemedicine, particularly in telesurgery. This marriage of medicine and telecommunications technology is now making it possible to perform surgery in some of the remotest places on and off the globe including distant battlefields, areas deep in the frozen arctic and space. These are places where access to advanced medical care was once negligible or non-existent.

Telepresence Surgery
Telepresence or telerobotic surgery is the most advanced form of telemedicine. It seeks virtually to recreate the presence of a remote surgeon at the patient’s bedside. This is accomplished with the help of sensors providing real-time tactile, visual and auditory information from the operating site and providing the surgeon with 3-D vision, stereophonic sound, tactile and force feedback.

In these operations, a surgeon sits at a computer console and the computer translates the his or her hand motion into the motion of the robotic instruments. The surgical robot, positioned at the patient's side, holds the camera and manipulates two or more surgical instruments. The computer console and surgeon can be positioned at a remote site thereby allowing the surgeon to operate on patients from halfway across the world.

Telepresence surgery was first developed by the US Department of Defense to allow surgeons to operate on wounded soldiers in the battlefield. In combat situations, 90% of all deaths occur before a soldier reaches a medical facility. These deaths are often preventable since the majority of injuries, such as hemorrhaging from major blood vessels, are treatable if operated on quickly. In telepresence surgeries, the soldiers are placed in vehicles equipped with the required robotics and communications equipment. While in transit, surgeons on aircraft carriers or other remote sites can perform life-saving surgeries, after which the soldiers are medically supported until they reach a military hospital.

Aside from the military applications, telepresence surgery also holds much promise in the civilian sector. One can envision a future where a team of surgeons operates on patients in third-world countries using telepresence vehicles that scour the country searching for people in need. Thus, telepresence would allow sophisticated surgeries to be performed by expert surgeons in places where neither the expertise nor the facilities can be found.

Much of the success of this technology, however, depends on the robots that serve as the remote eyes and hands of surgeons. Although a considerable number of developments in the field of telerobotics are in their initial phases, several well-developed systems are in use. Here we highlight two of these.

The Robots
Both systems are manufactured by California-based companies: the ZEUS® system by Computer Motion and the da Vinci™ Surgical System by Intuitive Surgical. Additionally, the ZEUS® system's robotic replacement for a camera holder, called AESOP®, can also be used independent of the full ZEUS® system.
Computer Motion’s AESOP® (Automated Endoscopic System for Optimal Positioning) has been in use since 1994. It allows the surgeon to guide the camera during laparoscopic procedures, thus eliminating the need for an assistant. While early versions of AESOP® were controlled using foot or hand switches, more recent versions are voice-activated. The robotic arm attaches to the side of a surgical table and can hold any rigid laparoscope.

The ZEUS® system is a full system for robotic surgery. Three arms are independently attached to the operating table: The AESOP® arm, holding the camera and two additional robotic arms each hold a surgical instrument. A variety of surgical attachments are available. The surgeon grasps a control for a robotic arm in each hand and orients himself/herself through a video monitor. The hand control gives the surgeon the ability to move with 6 degrees of freedom (DOF) at any scale. This allows for the performance of extremely precise movements, a valuable tool in situations where the slightest mistake could be catastrophic. A three-dimensional (3-D) view is produced by a video monitor that alternates between left and right images 60 times per second. A polarizing filter placed over the screen flashes between clockwise and counterclockwise filters in-sync with the alternating images. The surgeon then wears polarized glasses so that the left eye sees only left images, and the right eye sees only right images, producing the 3-D image.

The basic components of Intuitive Surgical’s da Vinci™ Surgical System are similar to those of the ZEUS® system. There are three arms, one holding the camera and two holding surgical instruments. The surgeon controls these arms and watches the images on the camera. The camera arm is foot-controlled. The robotic arms sit on a cart next to the surgical table, rather than being attached independently to the table, and each arm has seven DOF. The 3-D imaging system is a pair of binoculars worn by the surgeon that displays a different image to each eye.

The technology for robotic surgery is evolving. Current systems already provide some advantages over conventional laparoscopic surgery techniques through effective 3-D visualization, increased comfort for the surgeon, increased control over the camera and a good range of motion for the surgical arms. However, these systems are also expensive, bulky, lack some desirable features and require training. If robotic surgery is to become truly cost-effective and widespread, current features will need to be refined and additional features must be added. For this to happen, it is imperative that the limitations as well as avenues for future improvement of telesurgery are recognized and explored.

Limitations and Advances

Technical
It should first be recognized that laparoscopic surgery itself has many inherent difficulties which can be compounded by telesurgery. The skilled surgeon can manipulate his or her hand and wrist with virtually unlimited DOF, but even the most advanced laparoscopic systems today only allow 4-7 DOF. The lack of tactile feedback represents another major limitation of current telepresence technology. Furthermore, the feasibility and practicality of performing telesurgery depend not only on the ability to overcome the barriers of laparoscopic surgery, but also on the ability to transmit data rapidly and securely.

Advances in these areas are, in fact, being made at a rapid pace. The computer controlled camera systems not only eliminate the need for a “camera person” but also eliminate natural tremors thereby ensuring a stable field of vision. The AESOP® camera system has made significant advances in voice control which serve to decrease the latency between the surgeon’s thoughts and the robot’s action. One drawback of this voice control system is the requirement that each unit be voice-trained by each individual surgeon. The voice control also requires the surgeon to make continual vocal adjustments for example “right, right, left, right” which can be distracting to other members of the surgical team.
As already mentioned, one of the limitations of current robotic systems is the restricted motion offered by the hand controls. One way that the surgical robots compensate for this imperfection is through the use of multiple imaging techniques such as CT Scan and MR which guide robotic arms to the site of interest. In many cases, the computer guided movement is faster and safer than relying on the surgeon's unaided interpretation. Therefore, even with the limited DOF, the precision of a robotic arm may exceed that of a highly trained surgeon.2

Neither the ZEUS® nor the da Vinci™ systems currently provide haptic (tactile) feedback. This forces the surgeon to rely exclusively on visual feedback. A system that does provide haptic feedback, in addition to an integrated MR display, is the N euroArm™. N euroArm is a Canadian project currently under development at the University of Calgary with MD Robotics, the company that created the Canadarm in use at the International Space Station.7 This exciting new tool will further aid in creating the illusion of operating at the bedside.

As these technologies advance, the delay in transferring data from the surgeon to the robot, even in close quarters, becomes the limiting factor. During the New York–France telesurgery, this delay was less than 200 milliseconds. Swift data transfer was made possible by a high-speed data transmission system linking the equipment by a transatlantic high-bandwidth fiber-optic service running at 10 Mbits per second.3 While this technology is advancing rapidly, its distribution is not widespread, thus limiting the feasibility of conducting remote surgery in under-serviced areas. Transfer of large amounts of electronic data also raises a number of security issues. Furthermore, issues surrounding telesurgery include making contingency plans in cases of technical and equipment failure, assigning legal responsibilities in such cases and dealing with state/country-specific licensing requirements. It should be appreciated that these issues are far from being resolved and represent formidable challenges for the widespread adoption of telesurgical technologies.10

Cost:
The cost of “Operation Lindbergh”, once additional factors of distance were considered, was approximately $1 million (all figures US). Since the systems being tested today for telesurgery consist of a number of experimental technologies, it is difficult to accurately gauge their costs in the future. However, some estimates have been made. The da Vinci™ system, for example, used in telesurgical laparoscopic radical prostatectomy, would require an initial investment of $800,000 and an additional maintenance cost of $100,000 per year, adding approximately $1,500 – 2,000 to the cost of each procedure.

It is thought that the greatest cost savings will come from cutbacks in the number of operating room staff required. This, however, is not without some disadvantages. For example, residents do not represent additional costs and often act as surgical assistants. Telesurgical ventures in some areas, then, might restrict the depth and breadth of training available for residents.5

Future Directions
Despite the various limitations mentioned above, telesurgical technologies hold tremendous promise. It should also be recognized that telesurgery is only one aspect of the vast field of telemedicine; telementoring, teleproctoring (remote credentialing of trainees) and teleconsulting are just a few of the myriad of other applications of telemedicine.6,11 All of these sub-fields offer substantial avenues for enhancing patient care and medical education in both surgical and non-surgical specialties.6 They can help disseminate knowledge and expertise in surgical advancements to more disadvantaged geographic and socioeconomic environments. They can also aid healthcare entities in developing countries by broadening their knowledge about infectious diseases such as HIV and tuberculosis. As the advancements in telecommunications technology expand and the associated costs diminish, these various sub-fields of telemedicine, including telesurgery, are primed to make a significant impact on healthcare around the globe and beyond.6

References
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