Sajeev Kumar  Jacques Marescaux (Eds.)
Telesurgery
Developments in telesurgery are progressing at great speed. As a consequence, there is need for a broad overview of the field. This first-ever book on telesurgery is presented in such a way that should make it accessible to anyone, independent of his or her knowledge of technology. The text is designed to be used by all professionals, including surgeons, nurses, allied health professionals, and computer scientists, and not just medical practitioners.

In a very short time, driven by technical developments, the field of telesurgery has become too extensive to be covered by only a small number of experts. Therefore, Telesurgery has been written with chapter contributions from a host of renowned international authorities in telesurgery (see the Table of Contents and the List of Contributors). This ensures that subject matter focusing on recent advances in telesurgery is truly up to date. Our guiding hope during this task was that as editors of multiple chapters and authors, we could still write with a single voice and keep the content coherent and simple. We hope that the clarity of this book makes up for any limitations in its comprehensiveness.

The editors took great care that Telesurgery would not be merely a collection of separate chapters but would offer a consistent and structured overview of the field. We are aware that there is still considerable room for improvement and that certain elements of telesurgery are not fully covered, such as various surgical specialities, legal matters and reimbursement policies. A surgeon holds an array of sensors that is missing in the surgical robotics tools—sensors that can sense texture, temperature, force, pressure, blood pulse and smell! The new generation of tools for surgical robotics may include more sensing capabilities (such as the one explained in Chapter 11) for conveying to the surgeon information regarding the state of the tissue. The editors invite readers to forward their valuable comments and feedback to further improve and expand future editions of Telesurgery.
Books on theoretical and technical aspects inevitably use technical jargon, and this book is no exception. Although jargon is minimized, it cannot be eliminated without retreating to a more superficial level of coverage. The readers’ understanding of the jargon will vary based on their respective backgrounds, but anyone with some background in computers, health, and/or biomedicine should be able to understand most of the terms used. In any case, an attempt to define jargon terms is made in the Glossary.

This *Telesurgery book* has been organized systematically. The format and length of each chapter is standardized, thus ensuring that the content is concise and easy to read. Every chapter provides a comprehensive list of citations and references for further reading. There are numerous figure drawings and clinical photographs throughout, which illustrate and illuminate the text well, providing high-quality visual reference material. Particularly useful features of this text are that each chapter ends with a summary of salient points for the reader.

The book contains 15 chapters and begins with a brief introductory chapter explaining the concepts that are mainstay to telesurgery; subsequent chapters are built on those foundations. Within each chapter, the goal is to provide a comprehensive overview of the topic. The chapters on telementoring and law are deliberately placed in this first edition of the book to emphasize the fundamental importance of these topics. Nevertheless, its content is not inclusive, since opportunities arise progressively in this domain. The final chapter covers future directions for telesurgery.

This book would not have been possible without the assistsances of various people. We acknowledge and appreciate the assistance of all reviewers and Ms. Latika Hans, editorial assistant from Bangalore, India. We would like to thank all authors for making this possible through their chapter contributions. Their contributions in the not-too-distant future will be seen as major developments in health care.

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Introduction to Telesurgery

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1.1 Introduction to Telemedicine

Telemedicine is a method, by which patients can be examined, investigated, monitored, and treated, with the patient and the doctor located in different places. *Tele* is the Greek word meaning “distance,” and *mederi* is the Latin word meaning “to heal.” Though initially considered “futuristic” and “experimental,” telemedicine is today a reality and is here to stay. In telemedicine one transfers the expertise, not the patient. Hospitals of the future will draw patients from all over the world without geographical limitations. High-quality medical services can be brought to the patient rather than transporting the patient to distant and expensive tertiary care centers. A major goal of telemedicine is to eliminate unnecessary traveling of patients and their escorts. Data acquisition, storage, transfer, processing, and display represent the basis of telemedicine. Telemedicine is becoming an integral part of health-care services in several countries.

1.2 What Is Telesurgery?

Telesurgery, also called remote surgery, is performed by a surgeon at a site remote from the patient. Surgical tasks are directly performed by a robotic system controlled by the surgeon at the remote site. The word “telesurgery” is derived from the Greek words *tele*, meaning “far off,” and *cheirourgia*, meaning “working by hand.”

Telesurgery is surgery – actual cutting and suturing – performed by a surgeon at a console remote from the patient. Advanced communications technology allows the surgeon to manipulate endoscopic cameras and surgical robots to perform the surgery, while being remote from the operating room. Both the remote surgeon and the surgical team with the patient have exactly the same view of the surgical site.
Equipment is required at both the local and remote locations, and a secure communications connection is essential. As a safeguard, a surgical team is available to carry on surgery at the patient’s end.

In the early 2000s, several projects investigating the possibility and practicality of telesurgery were successful in performing complete surgical procedures on human patients from remote locations.

1.3 Does the Robot Actually Perform the Surgery?

Robots take surgery one step further. Typically, the surgeon sits at a console or workstation a short distance away from the patient. The workstation is capable of real-time three-dimensional (3D) imaging, enabling the surgeon to view the operative site inside the body, in detail.

Using hand and/or voice controls at the workstation, the surgeon manipulates robotic arms at the bedside, which are capable of wielding custom-designed surgical instruments and endoscopes (tiny cameras).

Complex software translates the surgeon’s hand movements into tiny, precise, tremor-free actions. The result is a surgery so precise that it cannot be replicated by the human hand.

1.4 Telementoring and Telestration

Telementoring uses advanced communications technology to enable an expert surgeon at a remote location to mentor a second surgeon in an operating room anywhere in the world. The expert surgeon can control the field of view (move the camera arm) from set-up and port placement, including telestration, through the entire procedure.

Telestration is an illustrative technique that allows a remote surgeon to use a drawing tablet to make marks on the local surgeon’s video monitor. Both the remote surgeon and the surgeon with the patient have exactly the same view of the surgical site. The remote surgeon can draw on the tablet to show where to make an incision or can highlight a tumor mass, for example.
1.5 Telesurgery: Foregoing Technologies

Telesurgery became a possibility with the advent of laparoscopic surgery in the late 1980s. Laparoscopy (also called minimally invasive surgery) is a surgical procedure in which a laparoscope (a thin, lighted tube) and other instruments are inserted into the abdomen through small incisions. The internal operating field may then be visualized on a video monitor connected to the scope. In certain cases, the technique may be used in place of more invasive surgical procedures that require more extensive incisions and longer recovery times.

Computer-assisted surgery premiered in the mid-1990s; it was the next step toward the goal of remote surgery. The ZEUS Surgical System, developed in 1995 by Computer Motion, Inc., was approved by the US Food and Drug Administration (FDA) in 2002 for use in general and laparoscopic surgeries, with the patient and surgeon being in the same room. ZEUS comprises three table-mounted robotic arms: one holding the AESOP endoscope positioner, which provides a view of the internal operating field, and the others holding surgical instruments. The robotic arms are controlled by the surgeon, who sits at a console several meters away. Visualization of the operating field is controlled by voice activation, while the robotic arms are controlled by movements of the surgeon’s hands and wrists.

Computer-assisted surgery has a number of advantages over traditional laparoscopic surgery. The computer interface provides a method for filtering out the normal hand tremors of the surgeon. Two- and three-dimensional visualization of the operating field is possible. The surgeon can perform a maneuver on the console, review it to be sure of its safety and efficacy, and then instruct the remote device to perform the task. The surgeon is also seated in an ergonomic position, with arms being supported by arm rests for the duration of the operation.

1.6 Further Developments

While the concept of telesurgery seems to be a logical technological progression – if a surgeon can perform a procedure from several meters away, why not from several thousand meters? – there is a major constraint that can lead to disastrous results during surgery, namely time delay. In the case of computer-assisted surgery, the computer console and remote surgical device are directly connected by several meters of cable; there is therefore virtually no delay in the transmission of data from the console to the surgical device back to the console. The surgeon therefore views his or her movements on the computer interface as
they are happening. If the surgical system was removed to a more distant site, however, it would introduce a time delay. Visualization of the operating field could be milliseconds or even seconds behind the real-time manipulations of the surgeon. Studies showed that a delay of more than 150–200 ms would be dangerous; satellite transmission, for example, would introduce a delay of more than 600 ms.

In order to make telesurgery a reality, expert surgeons would need to work with the telecommunication industry to develop secure, reliable, high-speed transmission of data over large distances with imperceptible delays. In January 2000, such a project, labeled “Operation Lindbergh,” began under the direction of Dr. Jacques Marescaux, co-editor of this book and director of the European Institute of Telesurgery; Moji Ghodoussi, project manager at Computer Motions, Inc.; and communication experts from France Telecom. Testing began on a prototype remote system (a modified version of the ZEUS Surgical System called ZEUS TS) in September 2000, with data being relayed between Paris and Strasbourg, France—a distance of approximately 625 miles (1,000 km). Once an acceptable length of time delay was established, trials began in July 2001 between New York City and Strasbourg.

On 7 September 2001, Operation Lindbergh culminated in the first complete remote surgery on a human patient (a 68-year-old female), performed over a distance of 4,300 miles (7,000 km). The patient and surgical system were located in an operating room in Strasbourg, while the surgeon and remote console were situated in a high-rise building in downtown New York. A team of surgeons remained at the patient’s side to step in, in case they were needed. The procedure performed was a laparoscopic cholecystectomy (gallbladder removal), considered the standard of care in minimally invasive surgery. The established time delay during the surgery was 135 ms, remarkable considering that the data travelled a distance of more than 8,600 miles (14,000 km) from the surgeon’s console to the surgical system and back to the console. The patient left the hospital within 48 h—a typical stay after laparoscopic cholecystectomy—and had an uneventful recovery.

Initially (as mentioned earlier), the surgical robotic products required both the patient and the surgeon to be in the same operating room. Two competitive products, however, appeared several years ago, which had the potential to further revolutionize the delivery of health care. The ZEUS Surgical System by Computer Motion and the da Vinci Surgical System by Intuitive Surgical were two products that could, in concept, allow the surgeon and the patient to be in two different geographical locations. In this way, the concept of surgery accomplished via telecommunication—telesurgery—could be realized.

While the concept of telesurgery was being refined, Computer Motion was also developing the Automated Endoscopic System for Optimal Positioning system (AESOP), a robotic platform for minimally invasive surgery designed
to hold the laparoscope required in such procedures. This introduced a new paradigm in robotics—that of robotically enhanced operations, where the robot would neither be autonomous nor mimic movements of the operator, but rather be an extension of the human operator. As surgeons and patients grew more comfortable with the concept of robots in the operating room, more capable next-generation technologies were introduced when new players such as Armstrong Healthcare and Intuitive Surgical entered the market for computer-assisted surgery. These were the foundations of robotics in medicine, standing in contrast to automotive and electronics industries where robotic technologies had already matured and become irreplaceable.

In 1992, Integrated Surgical Systems introduced ROBODoc for orthopedic surgery, specifically total hip arthroplasty. This robotic system allowed orthopedic surgeons to pre-plan their operations, while performing more accurate surgery. Today’s state-of-the-art da Vinci robotic system has proven its return on investment when used in laparoscopic radical prostatectomy (LRP), because it allows surgeons to perform the procedure less invasively within a time limit that is comparable to standard open procedures. Therefore, patients get the best of both worlds—positive outcomes with a small incision and quick recovery. Nonetheless, institutions paying upwards of US $1 million for a robotic system that can be used to perform laparoscopic cholecystectomy, Nissen fundoplication, etc., find it difficult to realize their return on investment— one reason why this market is not growing as rapidly as it might.

At the same time, the telesurgery platform used in Canada, and based on a much less capable ZEUS V2P platform—which has a standard endoscopic interface with 2D visualization, while da Vinci has full articulation and true-to-life 3D visualization—is an invaluable tool that allows expert surgical care to be provided to rural areas without the need to travel.

### 1.7 How Many Patients Have Had Robotic Telesurgery? Who Is Eligible?

While the exact number in worldwide use of telesurgery is not available, to date, the Canadian Surgical Technologies & Advanced Robotics (CSTAR) project team alone has performed more than 700 cardiac, thoracic, urologic, and general surgery robotic procedures. This team has also completed more than 50 surgical telementoring cases with remote navigation of the robotic camera arm and telestration.

CSTAR estimates that up to 25% of the 1700 single-bypass procedures performed annually at London Health Sciences Centre, Ontario, Canada, would be candidates for robotic surgery. Patients must be referred to a specialist by
their family physician. The specialist would recommend the patient to telesurgery center. Age, disease progression, anatomy, and general health are all deciding factors.

### 1.8 Patient Acceptance

Patients are very enthusiastic about the use of this new technology. They do not seem concerned about the use of robots. Most of all, they love the idea of smaller incisions and dramatically faster recovery.

Patient benefits are significant: smaller incisions, less scarring, less invasive surgery, shorter hospital stays, fewer complications, and faster recovery. Patients return to normal activities faster, resulting in increased quality of life as well as health-care savings. As the use of telesurgery service grows, patient and clinician perspective evaluations merit greater attention.

### 1.9 Scope of Telesurgery

Telesurgeons are already sharing their knowledge and techniques with colleagues around their respective nations and the world. They are also developing computerized training modules that can be shared through the Internet. Telementoring is an ideal method of sharing and training.

Other potential applications of telesurgery include:
- Assisting and training new surgeons
- Treating injured soldiers on or near the battlefield
- Performing surgical procedures in space
- Collaborating and mentoring during surgery by surgeons around the globe

### 1.10 Relevance of Telesurgery in Developing Countries

Ideally, every citizen in the world should have immediate access to the appropriate specialist for medical consultation. However, the current status of the health service is such that total medical care cannot be provided in rural areas. Even in suburban and urban areas, secondary and tertiary medical care is not uniformly available. Incentives to entice specialist surgeons to practice in suburban or rural areas have failed in many nations.
It is generally considered that the communities most likely to benefit from telesurgery are those least likely to afford it or to have the requisite communication infrastructure. However, this may no longer be true. In contrast to the bleak scenario in health care, Internet connections and computer literacy are fast developing, and prices are falling. Theoretically, it is far easier to set up an excellent telecommunication infrastructure in suburban and rural areas than it is to place hundreds of medical specialists in these places. The world has realized the future of telecommunications lies in satellite-based technology and fiber optic cables. Providing health care in remote areas using high technology is not as absurd as it may initially appear. Could even the greatest optimist have anticipated the phenomenal explosion in the use of computers in the villages of India?

### 1.11 Rewards of Telesurgery

Worldwide, there is difficulty in retaining surgeons in non-urban areas. Once the virtual presence of a surgeon is acknowledged through telesurgery, a patient can access resources in a tertiary surgical center, without the constraints of distance. Telesurgery also ensures maximal utilization of suburban or rural hospitals. Telesurgery may also avoid unnecessary travel and expense for the patient and the families and improves health outcomes.

It is also personally and professionally rewarding to know that each of us has played a role to increase access to surgical services and to improve quality of care. Few moments are as rewarding as receiving an anxious look from a patient in need and giving reassurances that access to the best surgical care is only a moment away.

### Summary

- Telemedicine allows a patient to be examined, investigated, monitored, and treated by a doctor located in a different place from the patient.
- In telesurgery, surgical tasks are directly performed by a robotic system controlled by the surgeon situated at a remote site.
- A mentor surgeon, while being away from surgical site, can assist the local surgeon through two advanced communication techniques: telementoring and telestration.
- Computer-assisted surgery has a number of advantages over traditional surgery.
With further development of telesurgery, providing surgical services in remote areas using high technology will soon become a reality.

**Bibliography**

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2.1 Introduction

The ability to obtain rapid data processing through computer-generated programs has a potential impact on all aspects of surgery. Computer-generated three-dimensional (3D) images allow visualization of structures from multiple points of view as well as development of interaction of virtual instruments with the virtual organs. Applications of this virtual reality systems provide new opportunities for education and training, preoperative diagnostics, preoperative planning, and intra- and postoperative applications.

On the other hand, digitalization of the surgical movements and images makes it possible to filter and exclude non-finalized movements (i.e., physiologic tremor of the surgeon) [8], resulting in greater dexterity and higher precision for performance of difficult tasks [5, 6, 21], which is one of the advantages of robotic surgery. Conversion of video images and surgical movements into electronic signals that can be transmitted over a distance introduced the concept of remote surgery.

In this chapter, we discuss several aspects computer-assisted and remote surgery as well as try to identify current limitations and future possibilities.

2.2 Education and Training

Virtual reality provides a safe training environment, where errors can be made without consequence to the patient, and the learning process is based on learning the cause of failure.

Just as military and commercial pilots, who perform a considerable amount of their training in simulated environments, the surgeons of the future may be trained with the aid of realistic surgical simulators and their skills assessed repeatedly and objectively.
This new approach to surgical training may shorten residency training programs, lower educational expenses, and possibly avoid the detrimental consequences of the early phases of the learning curve.

Surgical education can also benefit from the possibility of obtaining expert assistance from distance in the form of teleproctoring, telementoring, and teleconsultation. All these educational tools have been developed at Institut de Recherche contre les Cancers de l’Appareil Digestif (IRCAD)–European Institute of Telesurgery (EITS) in Strasbourg, France, where, integrated computer-based data access and surgical education through the Internet constitute the virtual university concept, realized in WeBSurg.

2.3 Preoperative Diagnostics

Current applications of virtual reality in preoperative diagnostics include gastroscopy, bronchoscopy, and colonoscopy. In addition, virtual colonoscopy has the unique advantage to allow “navigation” in the lumen of the bowel and views of the mucosa from any angle, as well as the possibility to pass through stenosis and even cross the colonic wall into adjacent structures [10]. These advantages might render virtual colonoscopy especially suitable for use in screening programs for colorectal cancer.

At IRCAD, we have developed systems based on the automatic reconstruction of anatomical and pathological structures from medical imaging such as CT scan and MRI. These systems automatically delineate anatomical structures with high contrast by combining the use of thresholding, mathematical morphology, and distance maps, for liver, upper airways, colon, and biliary tracts. We are currently evaluating the clinical applicability and possible advantages of using such systems. Preliminary results of our 3D virtual cholangiography system in 26 consecutive patients with suspected lithiasis of the common bile duct indicate that this procedure is feasible and sufficiently accurate for non-invasive preoperative diagnosis of lithiasis of the biliary tract [24]. We have also developed a software that, from CT scan and MRI images, provides accurate 3D reconstruction of anatomical and pathological structures of the liver (Fig. 2.1), as well as invisible functional information such as portal vein labeling and anatomical segment delineation according to the Couinaud classification [25]. Using the computer mouse, the surgeon can select various segmental resections to determine the optimum procedure (Fig. 2.2). An important impact that virtual reality imaging can have on liver tumor resection is the calculation of risk. The calculation of remaining liver volumes subsequent to partial hepatectomies is considered essential in predicting the future development of postoperative liver failure. On the basis of the 3D imaging and a patient-oriented
Fig. 2.1. Example of accurate 3D reconstruction of anatomical and pathological structures of the liver

Fig. 2.2. Selection by the surgeon of various segmental resections to determine the optimum procedure, with the computer mouse
risk analysis using objective parameters, virtual planning of hepatic resections could be helpful in improving patient selection and in reducing postoperative liver failure rates [20].

2.4 Preoperative Planning

Precise preoperative planning of the surgical procedure is essential for the success of complex surgical procedures. Preoperative planning requires precise location of the lesions and their anatomical relation to the adjacent tissues and vessels.

The development of digitized medical images through CT scan and MRI has represented a major advancement in medicine; however, detection of lesions or localization of vessels is sometimes difficult to process due to a variable image contrast between parenchyma and vessels, as well as to an important image anisotropy – the slice thickness being three times larger than the pixel width. Moreover, with conventional two-dimensional (2D) medical images, it is not easy to address important issues such as the spatial relationship of tumors with crucial structures, the evaluation of anatomic variants regarding vascular supply, and a volumetric and functional analysis to predict the risk of organ failure after resections.

Computer-assisted planning and simulation of operations have mostly been used in some subspecialties such as craniofacial surgery [12], neurosurgery, and orthopaedic surgery.

While in neurosurgery and orthopaedic surgery firm bony reference frame is available, for most procedures in general surgery, the virtual operation planning on the basis of 3D reconstruction of soft tissues has to overcome the obstacles of the inherent mobility and flexibility of the target organs.

2.5 Intraoperative Applications: Augmented Reality

Usually surgeons use CT, ultrasound (US), or MRI images to provide additional information reviewed during surgery; these images, however, cannot be readily integrated or overlaid into the surgical space. Augmented reality (AR) superimposes computer-generated images onto the real vision of the world in real time, providing additional help to facilitate the operative procedure. For instance, with AR, 3D reconstruction of the vessels can appear on the visible surface of the liver through a virtual transparency.
The deformation of abdominal organs under the heartbeat, respiration, or laparoscopic insufflation has limited the application of AR in general surgery. Recently, we reported the first image-guided interactive laparoscopic adrenalectomy in humans, using AR technology [18]. The case was that of a 45-year-old male patient, with a 1-cm Conn’s adenoma in the right adrenal gland. We used a 3D virtual reality (VR) software developed at our institution, which, from spiral CT-contrasted images, achieved detection, delineation, and reconstruction of the lesion, the adrenal gland, and other intra-abdominal organs of the patient. A conventional laparoscopic video screen and a second monitor displaying AR were used in the operating room. AR was generated by using seven different visible anatomical landmarks for registration of the virtual and the real image. Visible landmarks were chosen on the skin (ribs margin and three trocar sites) and inside the abdomen (inferior vena cava and two laparoscopic tools). Then, virtual images, manipulated by an independent operator at a distant site and connected through a fiber optic network, were superimposed onto the conventional laparoscopic view in real time. This interactive AR facilitated the laparoscopic right adrenalectomy by helping determine the correct dissection planes and localize the tumor, adjacent organs, and blood vessels. AR was most useful during identification of the main adrenal vein, whose location was accurately predicted by the AR imaging, leading to its safe isolation through a virtual transparency of the fatty tissue in which it was embedded.

To overcome the inherent limitations of this system, such as the need for manual tracking and a user-dependent accuracy, with more recent research we developed a new laparoscopic guidance system to replace manual procedures with automatic model registration and tool tracking for AR. With this system, patient model registration is achieved by using 20 radio-opaque markers stuck on the patient’s skin, while a CT scan is performed with the patient lying in the same position as required to carry on the surgical procedure. Two FireWire cameras are connected to a Pentium IV personal computer. Both internal and external anatomic landmarks are used to track structures under external and laparoscopic view. Experiments on inanimate models have been performed at our institution to measure the accuracy of the system, whereas preliminary clinical evaluation has been performed in two patients undergoing laparoscopic adrenalectomy. Automated tracking of patient’s anatomic structures and laparoscopic instruments has been feasible during the initial steps of the surgical procedure (external view) as well as under laparoscopic view. The user’s interface of this system offered a virtual transparency of all structures that had been modeled in 3D before the operation. The experiments on inanimate models showed a fair degree of precision of the tracking system, with an accuracy of 2 mm.

These latest experiments suggest that automated, real-time AR is feasible for abdominal operations.
Potential advantages of the use of AR include the adaptation of dissection planes or resection margins and the avoidance of injury to invisible structures; AR could facilitate performance of radical surgical therapy minimizing dissection and resection of neighboring tissues/organs and may be used as a tool for a more interactive form of telementoring by a distant expert. Furthermore, by enabling “through-skin” visualization of intra-abdominal structures, AR might improve safety and efficacy of various percutaneous techniques (i.e., radiofrequency liver tumors ablation).

2.6 Remote Surgery

Due to the important role of computer processing of data and digitalization of surgical movement, surgical robots are by all means an application of the concept of computer-assisted surgery. Robotic systems have computer programs that filter out hand tremors, while the chair’s arm at the surgeon’s console adds stability and comfort during the procedure, improving endurance. These features and the possibility to modulate the amplitude of surgical motions by downscaling and stabilization translate into smooth and precise surgical maneuvers, which has a great potential for improvement of dexterity and enhance precision [2, 7, 11, 22, 23].

Despite clinical trials verifying the potential advantages of robotic over conventional surgery being not yet available, feasibility and safety of robotic surgery have been reported by several independent groups. Our group performed laparoscopic robotic cholecystectomy in a total of 25 patients, with no robot-related morbidity, and operative time and patient recovery similar to those of conventional laparoscopy [16]. Cadiere and coworkers [3] reported a series of 146 patients undergoing robot-assisted laparoscopic surgeries, including anti-reflux procedures, gastroplasties, cholecystectomies, inguinal hernias, hysterectomies, and prostatectomies. Falcone and coworkers reported successful robotic assistance for reversal of tubal ligation using 8-0 sutures [6]. Robotic assistance has also been used for laparoscopic nephrectomy [3] and laparoscopic radical prostatectomy [9, 19].

Endoscopic cardiac surgery, including coronary artery bypass and mitral valve repair [4, 13], is a further important field of application of robotic surgery and will probably benefit by the possibility of operating on a beating heart through motion compensation, which would allow the surgeon to manage any moving structure with the same precision as if it were perfectly still [14].

In addition to enhancing human performance, robotic systems provide the unique ability to perform surgery in remote locations. Challenges to this concept are several, but the most important limitations have been the reliability (or qual-
ity of service) of the telecommunication lines and the issue of latency (the delay time from when the hand motion is initiated by the surgeon until the remote manipulator actually moves and the image is shown on the surgeon’s monitor). Due to the latency factor, it was believed that the feasible distance for remote surgery was no more than a few hundred miles over terrestrial telecommunications [14], while geosynchronous satellite systems, which have a latency of nearly 1.5 s, are considered unsuitable for performing long-distance surgery [23].

Since 1994, at IRCAD, surgeons and computer scientists as well as telecommunication and robotic engineers from Computer Motion (Santa Barbara, Calif.) have joined in a common effort aimed to verify the feasibility of surgery through long distances. This project was articulated in several steps, including testing the effect of artificially introduced time delays between the surgeon’s manipulations and the robotic effectors, experimental performance of laparoscopic cholecystectomy from remote distance on a pig model [15], and, finally, performance of a remote robot-assisted surgical operation on a human being. The project has led to the performance, on 7 September 2001, of the first robot-assisted laparoscopic cholecystectomy in a human, between New York (surgeons) and Strasbourg (patient) [17] (Fig. 2.3).
In the first series of our experiments, the maximum time delay was estimated at about 300 ms, which was compatible with safe performance of surgical manipulations. Subsequently, we measured a mean time delay of 155 ms over transoceanic distances when using dedicated asynchronous transfer mode (ATM) fibers [15]. This extremely short delay allowed the safe performance of a remote laparoscopic cholecystectomy in six pigs and provided the basis for the clinical application, which was carried out successfully without specific difficulties or complications due to the use of the teletransmission of the surgical procedure [17].

These results supported the use of existing high-bandwidth, dedicated telecommunication lines for performing intercontinental surgery on humans with adequate efficacy and safety.

More recently, Anvari and colleagues reported the establishment a remote telerobotic surgical service between a teaching hospital (St. Joseph’s Hospital in Hamilton, Ontario, Canada) and a community hospital (North Bay General Hospital) more than 400 km away [1]. Nissen fundoplications, sigmoid resections, right hemicolectomies, anterior resection, and inguinal hernia repairs have been carried out using a commercially available IP/VPN (Internet protocol–virtual private network). The results from their study corroborate our findings with the Lindberg operation and encouraged these authors to plan a surgical support network for provision of telementoring and telerobotic surgery between eight teaching hospitals and 32 rural communities in Canada over the next few years.

Technical feasibility and clinical safety, however, are not the only issues to solve to permit implementation of remote surgery into routine clinical practice. The use of remote surgery will indeed depend on a balance between real benefits and limitations.

Limitations are several. First, high-speed terrestrial ATM fibers are not yet available in most hospitals. Second, the cost of remote operations may represent a reasonable concern. In addition to the cost of the robotic system, which approximates US $1 million, other costs derive from the use of the teletransmission. There is no doubt that, if evaluated solely as the expansion of existing surgical practice, remote surgery is not certainly cost-effective. However, considering that the cost of technologies is expected to lower with time, and there is a potential to improve training and efficiency with enhanced outcomes, it is possible that remote surgery may prove less costly to healthcare systems in the future.

Since remote surgery may involve more than one state or country, conflicts of jurisdictions and legal issues such as whether the surgeon should or not be liable for errors related to delays in transmission or equipment failure, or whether a special consent should be obtained may also arise.
Despite limitations representing a serious concern, potential benefits are multiple and encourage the efforts to develop remote surgery. For instance, patients will be able to receive the type of treatment best suited to their condition ideally in any part of the world. Lack of expertise will not prevent, for example, exposure of the patient to new minimally invasive techniques. Furthermore, healthcare volunteers in developing countries may benefit from the assistance of experts from elsewhere. Likewise, challenging emergency operations in small rural hospitals could be performed by a young surgeon on call under the guidance of a distant expert from a major centre. Availability of expert surgeons might also very well help in remote areas, where military or scientific missions are being performed, or in remote islands.

In theory, remote surgery could also be useful in improving teaching and mentoring, in order to reduce the learning curve of surgeons for new procedures.

### 2.7 Future Developments

Virtual and AR systems can be used not only to teach surgical skills and judgment or facilitate intraoperative maneuvers, but also to rehearse procedures before performing them. With more perfected surgical simulators, in the near future, surgeons may work out the best operative procedure for each single patient and be able to repeat individual steps to improve surgical technique. The procedures can also be recorded and replayed from a robot automatically and at a distance. Combining AR with advanced robotics could guide the surgeons through technically challenging procedures and avoid injury to vital structures. The integration of physiology and anatomy in virtual 3D systems and simulators may also have a significant impact on research, since new procedures can be performed in a virtual patient and functional consequences or possible complications anticipated.

### Summary

- Virtual reality systems provide new opportunities for surgical education and training, preoperative diagnostics, preoperative planning, and intra- and postoperative applications.
- Current applications of virtual reality in preoperative diagnostics include gastroscopy, bronchoscopy, and colonoscopy.
- Augmented reality superimposes computer-generated images onto the real vision of the world in real time, providing additional help to facilitate the operative procedure.
Surgical robotics, which is an application of the concept of computer-assisted surgery, not only enhances human performance but also helps perform surgery in remote locations.

With more perfected surgical simulators, in the near future, surgeons may work out the best operative procedure for each single patient.

References

3.1 Introduction

As is the case with other surgical specialties, urologic practice has witnessed major breakthroughs throughout its history. Achievements such as the introduction of anesthesia in the 1840s and that of introducing penicillin in the 1940s have had a profound and lasting affect on the way urology is practiced. It is on this very same note that the revolution in information technology has to be seen, as current advances will undoubtedly again alter urology as we now know it. These exciting new frontiers have been made possible by the rapid expansion of the Internet, development in telecommunication infrastructures, an ever-multiplying computing power, and the increasing sophistication of robotics. Consequently, telesurgical urology became an inevitability, dictated not only by the incipient possibility but also by needs and necessities inherent to the specialty.

Urological procedures are characterized by being highly dependent on imagery and on a complex armamentarium of instruments and optics. Operations are performed in deep body cavities or confined spaces such as the pelvis and the retroperitoneum. It is because of features like these, and a rich tradition for embracing innovations, that urology lends itself to the implementation of telesurgery. The current chapter highlights the present and future roles of telesurgery and robotics in urology by addressing the following points:

- Overview of telesurgery and robotics in urology
- Master-slave robotic systems
- Remote surgery and telementoring
- Telemedicine and urology
- Future directions
3.2 Overview of Telesurgery and Robotics in Urology

The concept of telesurgery in urology is probably not new. Initial advances in telemedicine and telesurgery were however hampered by the constraints set by the limitations of computing power and lack of sufficient bandwidth to transfer the huge amounts of data necessary for such systems to be in place. It was therefore not until the last two decades, which have seen an explosion in computing power and great strides in the technology of information relay, that telesurgery emerged as a viable and practical management option. By definition, telesurgery is the ability to perform surgical procedures by means of a surgical robot actively controlled or programmed by a surgeon who is not in direct physical contact with the patient, the data being transmitted from the surgeon to the robot via telecommunication systems. The surgeon can hence be in the vicinity of the patient (in the operating theatre) or at a distance (another continent) while the procedure is being performed. Imperative to the latter situation is the integration of multimedia devices such as bidirectional (duplex) audio-visual telecommunication with robotic technologies and the existence of telecommunication systems capable of transmitting data with minimal delay.

Historically, the orthopedic and neurosurgical specialties led the way in the development of telerobotic surgery, as the nature of the tissues handled in these specialties allows for fixed anatomical landmarks that are easily imaged and can be used as reference points for image-guided procedures and stereotactic targeting [3, 25]. Contrary to this, the deformable nature of tissues and the mobility of organs in the parenchymatous specialties constituted an initial impediment to the implementation of telerobotics. Initial attempts at introducing robots in urology were therefore concentrated on prostatic surgery, owing to the prostate’s relatively fixed anatomical position in the pelvis. In 1989, at the Imperial College in London, Davies and colleagues showed the feasibility of using a modified industrial robot for transurethral prostatic resection [5]. Their concept was refined and put to clinical use in 1991, when they were able to carry out transurethral prostatectomies on five patients, marking the first time an active robot was used for resecting human tissue [6]. A second-generation robot under the name Probot was devised by the same group and also successfully applied clinically but never achieved widespread use [11]. The Probot and its predecessor were active robots in the sense that they proceeded autonomously once programmed and activated by the surgeon, working according to image-guided coordinates, which were fed to the system by the operator. Safety, which was a prime concern in the development of these systems, arose from the fact that these robots were programmed to precisely constrain motion to a predefined anatomical area marked by the surgeon, based on transrectal ultrasound (TRUS) measurements. This prevented injury to critical struc-
tures such as the external urinary sphincter and the bladder. Recent efforts have been made to integrate programmable robotic motion with laser resection of the prostate, to increase efficiency and the operative outcome of such procedures [12].

Other venues of image-guided robotic systems have been explored. Feasibility and preclinical studies have evaluated and reported on the potential of using automated and surgeon-controlled systems for placement of brachytherapy needles in prostatic tissue and for taking prostate biopsies. Rovetta et al. were the first to demonstrate the feasibility of a highly accurate automated transperineal prostate biopsy guided by TRUS and external video footage [31, 32]. Prototypes of CT- and MRI-guided systems have also been developed for prostate biopsies, such as the ones described by the Johns Hopkins and Harvard groups [7, 9]. Use of MRI-based technologies poses a further challenge, as the robot components had to be made of MRI-compatible materials that do not interfere with the imaging and vice versa [4].

Therapeutically, the use of brachytherapy in treatment of prostatic cancer is a well-established modality. Conventionally, radioactive seeds are placed in the prostate through a template and guided by TRUS [23]. TRUS allows for the creation of a three-dimensional model of the prostate and seeds are distributed herein according to an individual dose plan. Manual seed placement is a cumbersome and complex maneuver, and seeds have been known to migrate and cause serious side effects. Therefore, a number of groups have addressed these issues by creating image-guided robotic systems for automated seed placement, as robots have superior three-dimensional spatial accuracy, once fed with defined coordinates, and can position needles in any trajectory required. The Chinzei group devised and tested an MRI-guided and compatible surgical-assist robot for placement of brachytherapy needles along a predefined trajectory [22]. Others have described the use of TRUS-guided robotically assisted systems [10]. Undoubtedly, future refinement of these systems will improve the accuracy and efficiency of this somewhat complicated task and will minimize human handling of radioactive seeds and concomitant radiation exposure.

Noteworthy of mention is also the image-guided percutaneous access of the kidney (PACKY) robot. This portable device consists of radiolucent needle driver mounted on a remote center of motion (RCM) actuator. Guided by fluoroscopy obtained from an ordinary C-arm imager controlled by the surgeon, and using two plane views, a trajectory is calculated, and the robot advances a needle along this path to gain access to the renal collecting system [37]. This access can be used as a first step in percutaneous nephrolithotomy or for simple drainage of the collecting system with a nephrostomy tube. Manually, the procedure can be complex, as the needle has to be manipulated into a three-dimensional space using a two-dimensional imaging technique. The PACKY-RCM has proven quite reliable in achieving this task, with a success rate of
about 90% and has successfully achieved renal access in remote surgery procedures [1, 36, 37].

So far, the robots and prototypes mentioned have only had limited use in everyday clinical practice being mainly restricted to scientific and research institutes. Commercialization of robotics in urology came with the introduction of the automated endoscopic system for optimal positioning (Automated Endoscopic System for Optimal Positioning [AESOP], Intuitive Surgical, Sunnyvale, Calif.) in 1993. AESOP is a robotic arm with six degrees of freedom, designed to hold and manipulate a laparoscope according to voice commands, or hand/foot control. The system allows steady camera visualization of the changing operative field throughout the laparoscopic procedure. This diminishes the risk of motion sickness in the surgical team and enables solo laparoscopic surgery, even in complex procedures. Urological procedures performed with the help of the AESOP include laparoscopic radical prostatectomy [29], nephrectomy [24] and pyeloplasty [30]. A similar system, the EndoAssist (Armstrong Healthcare, High Wycombe, Bucks, UK), has also been used successfully. The robot is controlled by a head-mounted optical emitter worn by the surgeon. A sensor mounted on the video monitor registers the surgeon’s head movements and moves the camera accordingly [38]. It was, however, the advent of the master–slave telerobotic systems such as the da Vinci Surgical System and the ZEUS system (Intuitive Surgical) in the 1990s that elevated telesurgery into the public sphere.

### 3.3 Master-Slave Robots

Master-slave systems are designed to convey a surgeon’s movements, which are applied to joystick-like manipulators located at control a console, to a separate machine with robotic arms that replicates these movements via sophisticated end effectors connected to these robotic arms. The surgeon is therefore not in direct physical contact with the patient, thereby fulfilling the concept of telepresence surgery [34] and enabling the potential of performing operative procedures remotely. Of the different systems developed, the da Vinci and ZEUS telesurgical systems stand out as the most utilized robots. Originating from two different California-based manufacturers, the two companies merged in 2003 and since then, the da Vinci surgical system has dominated the market.

The da Vinci system offers a wide range of features that have rendered it an extremely potent surgical assistant. Composed of a master console that seats the surgeon comfortably (Fig. 3.1), the surgeon looks into a binocular eyepiece that enables high-resolution magnified (×5–10) stereoscopic three-dimensional vision emanating from two three-chip laparoscopic cameras aligned in paral-
For telemanipulation, the surgeon holds joystick-like handles (Fig. 3.2) that are ergonomically aligned in a position relative to the head and visual axis, so as to simulate the working position in an open surgical procedure. This gives the operator the illusion of being immersed in the surgical field and of being in direct control of the instrument tips. The slave unit of this system consists of three to four robotic arms, one of which controls the laparoscope, mounted on a movable base that is wheeled into position in proximity of the operating table. Once positioned, the surgeon’s manual commands (forearm, wrist and finger movements), which are sensed by high-resolution motion sensors, are transmitted to articulating end effectors (detachable and changeable surgical instruments with EndoWrist technology) (Fig. 3.3) connected to the robotic arms. Through an advanced computer system, movements are downscaled and refined by filtering out physiologic tremor, thereby enabling precise manipulation and suture placement even at a microsurgical level [35]. Drawbacks of the
Fig. 3.2. The joystick-like handle that transmits and translates the surgeon’s hand movements, via high-resolution motion sensors, to movements of the end effectors.

Fig. 3.3. Detachable and changeable end effectors with EndoWrist technology, which form extensions to the surgeon’s hands and by which tissue and instruments are handled intra-corporeally.
system include the initial investment premium and significant running costs. On a technical level, *da Vinci* lacks tactile feedback, which may cause some initial difficulties, but it can partially be compensated for by enhanced stereoscopic video imagery, which gives excellent visual cues of suture tension and tissue deformability.

Conventional laparoscopy, which was already an essential urological modality, poses certain limitations on many surgical procedures. The two-dimensional view of the laparoscope camera impairs spatial distance determination, and instrument maneuverability is limited to only four degrees of freedom, making intracorporeal suturing at best difficult and in some positions virtually impossible. The *da Vinci* system addressed many of these constraints, so although originally developed for cardiac surgery, the system was quickly seized upon by urologists, as it catered to many of the aforementioned shortcomings. Not long after the system was introduced, urologists reported on several surgical procedures carried out using the system or assisted by it to some extent. The system’s intuitive nature even allowed surgeons not experienced in laparoscopic surgery to join the bandwagon, being able to perform complex robot-assisted procedures such as radical prostatectomy successfully, albeit with protracted operative times [28].

Robotic laparoscopic radical prostatectomy has probably become the main domain of robotic surgery, with more than 5,000 procedures being performed worldwide [8]. Compared with conventional laparoscopy performed by an experienced surgeon, the robotic-assisted procedure probably has no advantages other than a shorter learning curve [8, 29]. A recent meta-analysis showed that robotic laparoscopic radical prostatectomy’s advantages included a short learning curve and better functional outcomes with regard to postoperative urinary continence [8]. Compared with open procedures, there is, however, a clear benefit with regards to shorter hospital stay, blood loss, postoperative pain, and recovery time [20]. Other urological procedures performed with the *da Vinci* system include dismembered pyeloplasty [26], partial nephrectomy [14], adrenalectomy [21], and cystectomy [33]. The list is growing, as different studies have evaluated the feasibility of robotic-assisted surgery for operations such as ureter reimplantation [27] and vasovasostomy [35]. This trend is also evident at the authors’ institute, where the use of the robot now is standard for the majority of pediatric pyeloplasties down to the age of 18 months and an ever-increasing percentage of prostatectomy patients.
3.4 Remote Surgery and Telementoring

The excitement created by the advent of telerobotic surgery was hardly dampened by the first reports of an intercontinental surgical procedure, or the Lindbergh operation, which was named after the American aviator Charles Lindbergh, who was the first person to cross the Atlantic by plane. This remote robotically assisted laparoscopic cholecystectomy was the world’s first successful transatlantic telesurgical procedure, where surgeons in New York City were able to operate a patient in Strasbourg, France, using the ZEUS surgical system. Signal transmission was enabled through a high-speed terrestrial fiber optic network using asynchronous transfer mode technology, which secured a minimal latency of about 150 ms [18, 19]. In urology, less spectacular yet equally important achievements have been published, such as the report of remote percutaneous access to the kidney in 1998 between Baltimore, Maryland, and Rome [1] and the world’s first telementored robotically assisted laparoscopic adrenalectomy between the United States and Europe in 1997 [13]. Successful telementoring of various other urological procedures has been reported, demonstrating the possibility of assisting a less experienced surgeon to perform complete robot-assisted laparoscopic procedures when guided by an expert. The expert controls the laparoscope and may use a telestrator, which is a sketch pad that allows the mentor to mark structures and regions of interest on the operator’s monitor [2, 15, 16]. Importantly, and with the use of master-slave telerobotic systems, future telementoring may involve the expert taking control of events at junctures that are too technically demanding for the trainee and the ability to override control in order to avert complications and injury. Remote surgery and telementoring hold great promise for the advancement of global healthcare, as this technology may provide expert surgical care to patients in remote geographical areas and may improve the standards of surgical training by allowing junior doctors to be mentored by authorities in their respective specialties, regardless of where they are stationed. Furthermore, teleproctoring or the ability to assess and evaluate trainees from a distance, for the purposes of accreditation, may provide for a uniform universal standard of care and assessment of skills [17].

Implicit to the implementation of remote surgery is the access to telecommunication infrastructures of sufficient bandwidth, which are still not universal. Surgeons can compensate for a latency of up to 300 ms; delays beyond this lead to movement overshooting and degradation of task completion [37]. On the other hand, delays of up to 1 s have been deemed tolerable for telementoring [13]. Other limitations include the legal aspects and issues of jurisdiction and liability when performing remote surgery. These matters need to be addressed internationally before telesurgery can be realized on a global scale.
3.5 Telemedicine and Urology

The role of telecommunication systems cannot be understated in a chapter dealing with urological telesurgery. Other than bearing the vast amounts of data needed to perform remote surgery, these channels, be they Internet, satellite links or fiber optic networks, have or are in the process of creating virtual urological communities that are able to communicate, meet, consult, and mentor each other beyond the constraints of time, distance, and travel. With this comes dissemination of highly specialized expertise beyond the physical confines of university hospitals and scientific institutes, potentially benefiting global healthcare access and improving medical education. An example to draw on is the picture archiving and communication system (usually known by the acronym PACS), which is becoming an integral part of modern uroradiologic services. Other than storage and management of medical imagery, PACS allows off-site viewing and consultation (teleradiology), whereby the same information can be accessed by more than one user simultaneously and enables telestration (using a pointer to mark out regions of interest on another monitor showing the same image) and telediagnostics. Systems such as this allow real-time teleconsultation and access to expert medical opinion, which conventionally is confined to referral centers. Using systems less advanced yet with the same basic principle as PACS, it has been shown that tele-uroradiology not only is feasible, but also enhances the quality of care given to patients with urolithiasis, owing to an efficient and easy transfer of images from the referring urologist to specialized stone centers.

The Internet now also constitutes a major and vital repository for urological information and education. Virtually all scientific institutes, universities, medical manufacturers, pharmaceutical companies, and urological societies can be accessed on the net. Hence, information in all variations can be shared instantaneously and communicated to practitioners and the general public worldwide. At the authors’ institute, telerobotic procedures are regularly streamed online, allowing professionals cleared with a secure access code to follow operations via virtual private networks for educational purposes. Other facilities include the access to medical literature and scientific databases such as MEDLINE (Medical Literature Analysis and Retrieval System Online) and the Cochrane Collaboration, which have facilitated research and access to evidence-based medicine. For the urological community as for others, the Internet has also become a hub for communication, through which online announcement of medical conferences and events are posted.
3.6 Future Directions

Urological telesurgery is still in its infancy, but if the pace of events leading to this point should be taken as any indication, it is unquestionable that major refinements and revelations are in store. Robotic systems of the future may incorporate the use of MRI, CT, or ultrasound imaging in addition to the visual guidance now available. It is expected that machines of the future will become less bulky and easier to set up in standard operating theatres. Robot-related expenditures, which have been a major hindrance to the wide-scale spread of such technology, may become less of an issue, as the increasing demand and projected competition may ultimately lead to more reasonable prices. Interesting research into the field of haptics or “force feedback technology” is being conducted; this will confer telerobotic surgery the sense of touch, which until now is largely not available. Such an interface may also be used in the development of virtual reality simulators for surgical training, in which trainees will be able to manipulate objects such as endoscopes and instruments virtually in computer-created models of patients. Urological accreditation of the future may therefore come to rely on the concepts now used in the training of commercial airline pilots, and would be a step welcomed by the medical community and the patients alike. It may even prompt the rendering of Halsted’s promulgation of “see one do one, teach one” obsolete, only to be replaced by a more modern version of “see one, simulate one, do one, telementor, and teach one,” which is less concise or rhymed but more befitting the age of technological advance and capabilities we live in.

Summary

- Rapid expansion of the Internet, development in telecommunication infrastructures, an ever-multiplying computing power, and the increasing sophistication of robotics helped telesurgical urology emerge as an important surgical procedure.
- Telesurgery involves performing surgical procedures by means of a surgical robot, actively controlled or programmed by a surgeon who is not in direct physical contact with the patient, the data being transmitted from the surgeon to the robot via telecommunication systems.
- Master-slave systems convey a surgeon’s movements, applied to joystick-like manipulators located at control console, to a separate machine with robotic arms; the surgeon is not in direct physical contact with the patient.
- Though urological telesurgery is still in its infancy, major refinements and revelations are in store.
References

Lung Cancer Brachytherapy

Lung cancer is the leading cause of death in men and has surpassed breast cancer as the most frequent cause of death in women [8]. Surgical resection is the treatment of choice, but only a third of patients who present with early disease are eligible for a curative resection [48]. Open surgery provides ready access and optimal visualization of body cavities; however, it has a higher rate of morbidity compared with minimally invasive techniques. Other options need to be developed. Brachytherapy is a form of radiation therapy of tumors delivered by the direct placement of a radioactive source into a tumor or tumor bed. It provides an option that avoids major surgery, chemotherapy, and the uncertainty of tumor motion, while the patient receives external beam radiation. It also avoids conventional multiple external beam radiation fractions that occur over several weeks.

Endoluminal high-dose rate (HDR) brachytherapy is used routinely in the palliation of lung cancer [79]. The radiation source is placed through the tumor with a bronchoscope and then removed. An electromagnetic-navigated bronchoscopic approach to a small peripheral tumor has recently been described by Harms et al. [20]. A single patient with medically inoperable non-small cell lung cancer (NSCLC) in the right upper lobe was treated with external-beam radiotherapy (50 Gy) and navigated endoluminal brachytherapy (15 Gy). Bronchoscopy was performed with electromagnetic navigation, using a microsensor mounted on the tip of a dedicated catheter placed within the working channel of a bronchoscope. Endobronchial ultrasound (EBUS) was performed to confirm the exact position at the centre of the lesion. HDR brachytherapy (370 GBq iridium-192) was applied. Complete remission was found during follow-up (12 months).
HDR brachytherapy has also been delivered to lung cancers using a percutaneous route [6, 32, 66, 67]. Most tumors either decreased in size or there was a reduction in pain; however, a significant number of patients developed a pneumothorax [6].

Low-dose rate (LDR) interstitial brachytherapy is another form of radiation therapy, with dose rate ranging from 0.1 cGy/min to 0.1 cGy/h. The radioisotopes most commonly used include iodine (I-125), palladium (Pd-103) or gold (Au-193), and when placed inside titanium shells are called “seeds.” The overall size of the seed can vary slightly depending on the application. Radioactive isotopes have a characteristic that is very critical for this application – the dose rate measured at a distance from a point source declines as a function of the inverse square of the distance from the source. Since these sources emit very low radiation that is absorbed by the tissue immediately surrounding the seed, the exposure of healthy tissue to the radioactive source is considerably reduced. These permanent implants allow more precise delivery of radiation and easier adaptation to the tumor shape than is possible with external radiation [18, 24], and a higher dose can be delivered to the tumor volume with less damage to the normal lung. The seeds are implanted into cancerous tissue, using long and hollow needles, which have small outer diameters and at least one sharp end to allow penetration through the tissue. The seeds are manually loaded into the needle barrel and are spaced from each other by one or more inert spacers that are implanted together with the seeds. A small amount of bone wax is placed on the tip of the implant needles to prevent the seeds from falling out and to prevent the tissue from entering the hollow needle. A plunger inserted in the needle behind the last seed is used to release the bone wax and drop the seeds.

The goal of the brachytherapy procedure is to implant the seeds into the malignant tissue such that they are uniformly distributed in a particular pattern, according to a dose or distribution plan selected by the physician. In general, a series of aligned seeds is introduced with each insertion of the needle. To achieve this goal, each needle must be accurately inserted into the tissue following a particular path and reaching a specified depth. Accurate placement ensures that all seeds are located within the target region and avoids over- and under-radiated spots. Once the needle is accurately located, the seeds and spacers are dropped from the tip of the needle, as the needle barrel is retracted towards the stationary plunger. In order to improve the accuracy of needle placement, coordinate grids are often used to guide the needle insertion, while real-time ultrasound (US) images are used to guide the needles to the desired depth. In a common prostate brachytherapy procedure, 80–100 seeds are implanted into the prostate, using between 20 and 25 needles.

The biggest challenge in delivering radiation therapy is achieving an accurate dosage of radiation. Since the entire treatment is very complex, careful consideration of the planning and delivery is required in order to optimize re-
sults and minimize side effects [59]. During a brachytherapy procedure, this challenge translates into accurately placing the seeds, since small deviations in seed alignment can create significant areas of over- and under-dosage. Some of the causes for seed misplacement are as follows:

- Difficulty in needle access of the surgical site, caused by the presence of bone structures, major nerves, or blood vessels. Extensive clinical experience is required to achieve the proper access [72].
- Difficulty in needle placement, which includes accurately locating and orienting the needle prior to the penetration, as well as achieving the proper penetration depth [53].
- “Unstable holding of the plunger relative to the needle during needle barrel retraction.” Small unintended movements of the plunger relative to the barrel can result in inaccurate placement of the seeds and a reduction in the effectiveness of the treatment.
- “Differences in tissue location and size between dose planning and seed implantation [58].”
- “Patient movement during the procedure, which can be caused by tissue shift, breathing, heartbeat, or swelling of the organs.”

An additional disadvantage of the traditional method is the amount of time that the surgical personnel are exposed to the radiation source. Manual insertion of the needles can take a long time, since it sometimes requires as many as 20 insertions prior to achieving accurate placement [73].

Hilaris and Martini reviewed the Memorial Sloan-Kettering Cancer Center experience in over 1,000 patients who received intraoperative (LDR) brachytherapy via an open thoracotomy [24]. The use of encapsulated I-125 seeds greatly reduced the radiation outside the treatment volume and minimized the medical and nursing staff exposure. However, the intraoperative radiation exposure to the surgeon and the need for a large open thoracotomy with only a modest survival advantage have hindered its clinical acceptance.

There is only a limited experience with LDR interstitial brachytherapy under bronchoscopic, fluoroscopic, and CT guidance [24, 48, 55, 70, 76]. Although the CT-guided percutaneous approach is feasible, it is limited to small and soft tumors in the periphery of the lung, and the optimum radiation dose distribution frequently cannot be achieved due to the bony structures in the chest wall that inhibits precise seed implantation. The risk of injury to proximal mediastinal structures, bleeding, and lung collapse also limit this technique to only small tumors adjacent to the chest wall.
4.2 Robotic Minimally Invasive Thoracic Surgery

The momentum for minimally invasive thoracic surgery has been growing. Minimally invasive surgery (MIS) employs the use of instruments through small incisions in the patient’s chest or abdomen to remove cancers. The procedure relies on endoscopic video images for guidance and the surgeon for instrument manipulation. Procedure-related intraoperative complications can be dealt with immediately. Compared with a thoracotomy, video-assisted thoracoscopic surgery (VATS) offers patients a shorter length of stay, less pain, and a quicker recovery, without compromising the adequacy of the operation [51, 52]. Thousands of VATS lobectomies have been performed since it was pioneered in 1992, but currently most lobectomies are still performed via a thoracotomy. Although most lobectomies could be performed with VATS, less than 5% are currently performed that way due to limitations of minimal access, restricted maneuverability of instruments, and impaired two-dimensional (2D) visualization. The techniques are difficult to learn and therefore not used as often.

Surgical robots have been shown to improve MIS efficiency by providing superior three-dimensional (3D) magnification, enhanced dexterity, and improved precision by tremor filtration and motion scaling [7, 13, 57, 61]. To the surgeon, surgical robots also offer improved ergonomics, instrument dexterity during VATS, and the opportunity to operate via telesurgery at a safer distance from the radioactive source [56]. Surgical use of robotics, or computer-assisted surgical systems (CAS), has evolved over the last 10 years for the treatment of chest diseases; however, significant development has really occurred only in the last 3–4 years. Moreover, because of this modest experience, robotic thoracic procedures currently take more time than non-robotic cases and, thus, are more expensive. The surgical learning curve appears to be steep, especially for the more complex procedures [34]. As surgeons gain greater experience and the complexity and cost of the equipment are reduced, we should expect to see greater use of CAS in thoracic surgery.

The ZEUS Surgical System is the world’s first and only telesurgical robotic platform, able to provide surgical care at a distance [12]. It has the potential to interface with surgeons in any part of the world and beyond. It is an ergonomically optimal environment and interfaces with a networked operating room and surgical devices. It was developed and manufactured by Computer Motion. With the recent corporate restructuring, Computer Motion merged with its competitor, Intuitive Surgical. The ZEUS robotic platform has been replaced by the da Vinci platform.

Intuitive Surgical’s da Vinci Surgical System combines superior 3D visualization along with greatly enhanced dexterity, precision, and control, in an in-
tuitive, ergonomic interface with breakthrough surgical capabilities [13, 33, 57, 61]. By enhancing surgical capabilities, the robots reduce trauma to the body, reduce blood loss and need for transfusions, decrease postoperative pain and discomfort, lower the risk of infection, decrease hospital stay, allow for faster recovery and return to normal daily activities, reduce scarring, and improve cosmesis. The robots also allow the surgeon to perform minimally invasive procedures more safely, by allowing immediate access to vital structures and the ability to repair injuries that may occur during the therapy.

4.3 Adjuvant Brachytherapy for Lung Cancer

The recent increase in MIS has also renewed an interest in the role of adjuvant brachytherapy for lung cancer [5, 9, 14, 16, 41, 62, 68, 80]. Following resection of small lung tumors (T1N0), intraoperative I-125 seeds have been implanted with Vicryl mesh along the resection margins [9, 14, 16]. The technique appears to be safe and appears to reduce local tumor recurrence rates, but long-term results are required. Pisch et al. have reported on the da Vinci robot’s ability to suture in brachytherapy seeds into a porcine lung [62]. MIS wedge resections were performed in the upper and lower lobes. Dummy I-125 seeds embedded in absorbable sutures were sewn into the resection margin with the aid of the da Vinci robotic system without complications. The robotic technology allowed direct placement of radioactive seeds into the resection margin by endoscopic surgery. This renewed enthusiasm for lung brachytherapy has resulted in a multi-institutional randomized phase III study of sublobar resection versus sublobar resection plus brachytherapy in high-risk patients with NSCLC, sponsored by the American College of Surgeons Oncology Group (ACOSOG 4032) [3].

It is believed that earlier detection of lung cancer should translate into more effective treatment. Lung cancer screening has been revived with various reports showing an advantage of low-dose CT over chest radiographs in detecting smaller-size tumors, and at an earlier stage [4]. Studies have found that 80% of all the tumors found were of stage I, with an estimated 8-year cure rate for resected lung cancers of 95% [22, 23]. This suggests that a higher proportion of deaths from lung cancer can be prevented by CT screening followed by early resection [22, 23]. The gold standard therapy for NSCLC is a lobectomy, while lesser resections are reserved as a compromise operation for high-risk patients [19, 71]. Earlier studies have suggested that sublobar resections for stage I tumors are complicated by increased loco regional recurrence rates [19, 40]. The increased identification of small NSCLC tumors by CT scan is leading many surgeons to question the appropriateness of lobectomy for these tumors. There
is an increasing interest by many surgeons to use sublobar resection as the new standard for patients with small peripheral lung cancers [35]. Intentional sublobar resection for small lung cancers (T1N0) has been performed using minimally invasive techniques with equivalent results [15, 17, 37–39, 60, 85]. Recently, intraoperative brachytherapy on the resection staple line has been shown to significantly decrease the local recurrence rates associated with these limited resections [5, 14, 16, 41, 68]. Future directions in the management of early lung cancer will include MIS surgery combined with brachytherapy.

4.4
Robot-Assisted Minimally Invasive Brachytherapy for Lung Cancer

The future of lung cancer therapy may include the placement of individual brachytherapy seeds minimally invasively into lung cancers, using a robot-assisted brachytherapy seed delivery system. The prerequisites for such an approach are (1) a method to localize the tumor intraoperatively, (2) a means of tracking and guiding the needle in real time, (3) 3D images of the tumor from which the dosimetry will be planned (based on the tumor contours), and (4) a brachytherapy seed delivery device for the robot.

4.4.1
Lung Tumor Localization

For minimally invasive brachytherapy to be performed in the lung cancer, it is imperative that some form of image guidance be incorporated for instrument tracking and tumor localization. Tumors that are deep within the lung cannot be seen with the thoracoscope. The procedure is performed through small incisions, and it is not possible to palpate the nodules either manually or with standard MIS instruments [75]. Current tumor localization techniques include methylene blue staining and the insertion of a hook wire [10, 31, 42, 50, 64, 83]. These methods have been found to be cumbersome, have a high failure rate, and increase medical risks and litigation [21, 46, 74]. A method that can reliably localize lung nodules minimally invasively during an intraoperative procedure is needed. Although lung tumors may be readily seen using CT imaging, intraoperative CT machines are not available, and there is often a delay of several months between a preoperative CT scan and the actual surgical procedure. From a global perspective, intraoperative US imaging appears to be the modality of choice. US does not expose the patient to radiation as a CT does, and it can achieve real-time dependable dose plans for brachytherapy treat-
ment. MIS US probes are now available from many manufacturers, enabling its use in guiding minimally invasive thoracic surgeries.

### 4.4.2 Needle Tracking and Guidance

Much effort has been put into overlaying real-time navigation information with preoperative information to serve as image guidance during procedures. A tracking device can be attached to the tool and its position displayed on the preoperative image (e.g., MRI, PET, and CT). Kevin Cleary’s group at Georgetown University has developed a system for surgical assistance, incorporating magnetic tracking and CT image overlay for targeting internal organs such as the liver [11]. Virtual reality image overlays for brachytherapy have been studied by Roeddigter’s group in Germany [82]. Their work uses preoperatively acquired image data that are then displayed together, with the position of the tracked instrument on a transparent overlay that can be put on top of the patient. An ongoing challenge with the static preoperative CT images is the reduced navigational accuracy due to respiratory motion. Strides have been made with electromagnetic tracking for abdominal interventions [36, 63, 69, 84, 87, 88]. However, no system exists today that can compensate for lung motion around lung tumors.

Recent advances in electromagnetic tracking systems have led to the miniaturization of the sensors and better immunity to nearby metallic objects. For example, the microBIRD tracking system (Ascension Technology) features a six degree-of-freedom DC magnetic tracker, with a sensor diameter of just 1.3 mm. An electromagnetic transmitter situated outside of the body generates a weak spatially varying magnetic field that can be measured by the sensor to dynamically compute position and orientation. Field distortions caused by nearby conductive metals, which significantly affected earlier AC systems, have been minimized through the use of DC pulses.

### 4.4.3 Brachytherapy Treatment Planning

CT simulation has been the standard for treatment planning in many modern radiation therapy centers; however, CT simulation is not readily available intraoperatively in most countries. The literature on 3D US simulation with permanent brachytherapy seed implantation treatment planning in lung cancer is limited [43]. The number of permanent seeds used in a given tumor volume and the angle of brachytherapy needle entry for a given tumor mass are yet to be defined. The dosimetry plan for MIS interstitial brachytherapy seeds in lung tumors is unknown. Standard needle templates used in prostate brachy-
therapy are not usable for intrathoracic tumors, due to the bony rib cage and the restriction of only one entry port as a component of MIS. New approaches need to be developed.

4.4.4 Brachytherapy Seed Delivery System

Many researchers have been working on ways to improve brachytherapy procedures. Currently, the most common usage of brachytherapy is in the treatment of prostate cancer and hence many of the developments have focused on this area. The contributions found in the literature can be summarized as follows: control of the relative motion between the hollow needle and the plunger [30]; accurate positioning and orienting of the needle prior to penetration [53, 73, 81]; drivers for needle penetration [49, 72]; real-time image guidance during needle insertion [11, 81]; force feedback during needle insertion [49, 84]; and tissue motion compensation [1, 2, 25]. However, none of these devices is currently available in the market due to their complexity and lack of regulatory approval for clinical use. Additionally, they are designed only for percutaneous needle insertion, and most have been designed specifically to treat tumors located in the prostate. The process of implanting seeds within lung cancerous tissue could greatly benefit from the use of minimally invasive robotic systems; however, an instrument that can be attached to these systems for brachytherapy is not currently available.

4.5 System at Canadian Surgical Technologies & Advanced Robotics

Our work at Canadian Surgical Technologies & Advanced Robotics (CSTAR) has focused on six areas:

1. Development of a lung tumor model and robotic brachytherapy test bed
2. Development of 3D US imaging for lung tumors
3. Design of a delivery system for robotic brachytherapy
4. Robot-assisted brachytherapy using the ZEUS platform
5. Development of an electromagnetic navigation system for precise needle insertion
6. Dosimetry planning

In order to carry out our in vitro experiments, we developed an experimental test bed to assess the feasibility of robot-assisted minimally invasive lung
brachytherapy, when compared with other more traditional methods [78]. The system consists of a VATS box, surgical robotic arms, the seed injector, a US machine, an electromagnetic tracking system, video monitors, a computer, and an endoscope (Fig. 4.1). The ZEUS Surgical System consists of three arms, two for instruments and one for the endoscope. The camera arm is controlled tele-surgically using a remote pendant. The instrument arms mimic the motion of hand held instruments, which are manipulated by the surgeon from the remote console. One of the arms can be used to hold and manipulate the US probe, while the other holds the seed injector. The Automated Endoscopic System for Optimal Positioning (AESOP) positioning arm moves an instrument by following simple commands (up, down, left, right, in, and out) that indicate the direction in which the tip of the instrument should move. The motions are controlled by pressing the corresponding buttons on a remote pendant or by voice activation, which causes a discrete motion in the direction of choice. The seed injector was designed to be attached to either of these robotic systems, in order to accurately control the motion of the needle assembly and deploy radioactive seeds [77]. In this setup, the microBird DC electromagnetic tracking system was used to track the location of the needle and the US.
A technique for creating intraoperative, near real-time, 3D US images of human lung nodules using MIS techniques was developed [27]. Multiple 2D US images of a subpleural nodule scanned intraoperatively were reconstructed into 3D images. We adapted the HDI 5000 LapL95 laparoscopic probe to a transducer holder containing a mechanical motor attached to a standard computer. The modified probe was used to thoracoscopically detect and remove a subpleural nodule through three 12-mm incisions. The device is easy to use, and the images accurately identified the tumor. The images correlated well with the preoperative CT scan and final pathology. Intraoperative 3D US proved to be feasible in localizing invisible or no palpable lung nodules in near real time and provided an accurate representation of the anatomy during thoracoscopic lung surgery. This is the world’s first example of thoracoscopic 3D US imaging of a human lung nodule (Fig. 4.2) [27].

An *ex vivo* lung tumor model, using excised porcine lung and agar tumors, was developed to provide a means of verifying 3D US images and to provide a teaching tool for intraoperative lung US techniques [28, 29]. Various size spherical tumors were made from agar and were inserted through incisions on the underside of an excised porcine lung. The average coefficient of variation

![Fig. 4.2. Three-dimensional US image of a human lung tumor](image-url)
and volume error was 11.2 and 12.9%, respectively, and tumor volume error decreased as the tumor size increased [26, 29].

In order to deposit radioactive seeds inside a lung tumor within a minimally invasive environment when the target tumor is located within the lung and thus is not visible, we developed the InterNAV application [65]. It incorporates the US image, the information from the electromagnetic sensors, and the calibration data to provide the user with enough information to accurately guide and position a needle at a desired target. A graphical user interface (GUI) was developed as a front-end for the InterNAV application (Fig. 4.3). The InterNAV GUI consists of three views (Ultrasound, World, and depth views), as well as the Systems Control dialogue. Collectively, these components provide a wealth of information and functionality. Not only does the GUI allow the user to visualize the anatomical area of interest, but it also allows the user to select the appropriate target and provides all the information required to guide the needle towards the target in a quick and intuitive manner.

In order to implant brachytherapy seeds into lung tumors, we developed an injector for robot-assisted brachytherapy that can be attached to any of the arms of the ZEUS robotic system for MIS [77]. The device is then used to accurately deploy the radioactive seeds within the cancerous tissue. An initial

Fig. 4.3. The InterNAV GUI consists of three views (Ultrasound, World, and depth views) as well as the Systems Control dialogue
prototype of the device has been built and has been tested (Fig. 4.4). This device allows brachytherapy to be performed through small incisions in the patient’s body in a minimally invasive manner, and it allows the position and orientation of the needle to be adjusted inside the patient’s body prior to penetrating the target tissue. The MIS approach allows better access to organs inside the thoracic cavity and therefore can safely avoid vital structures. The injector can easily penetrate the more scirrhous tumors, and the remote actuation of the needle retraction system reduces the exposure of the clinician to the radiation source.

Our initial proof of principal experiments demonstrated that permanent interstitial brachytherapy seeds can be safely and reproducibly inserted using an MIS technique with the assistance of the ZEUS robotic system and intraoperative US into in vivo porcine lungs [47]. There were no problems with bleeding or air leaks. The ZEUS system performed well and was able to remotely manipulate the US transducer and needle to allow deployment of the seeds (Fig. 4.5). The US images were of good quality and visualised the needle insertion and seed deployment. There was no evidence of seed embolisation in the two animals up to 3 months. Interstitial brachytherapy seeds can be safely inserted into lungs, using the ZEUS robotic system with 2D US image guidance.

We also compared the accuracy, effort, and time needed to place seeds next to a target using a manual method, VATS, and the ZEUS robot [45]. Our brachytherapy seed injector was used and attached to one of the ZEUS robotic arms [77]. Four different people inserted dummy brachytherapy seeds into clear agar gelatin cubes containing a 1.6-mm stainless steel ball serving as the target. As anticipated, the manual technique is the most accurate, least traumatic (requiring less needle punctures), and the fastest method of inserting seeds into tumors. However, ZEUS robot-assisted brachytherapy was less traumatic and faster than was the VATS technique.

Further experimental results showed that the InterNAV electromagnetic navigation system improved the performance of minimally invasive brachytherapy procedures in terms of effort and median tissue trauma, while also showing promise in improving the accuracy of seed deployment [44]. With manual insertions, the navigation system offered no advantage in time, al-
though it led to a reduction of the number of attempts and an improvement in accuracy. The benefit of a guidance system was manifested only when visual information becomes limited in MIS scenarios, whereas the intuitive 3D spatial perception afforded by the open manual technique has made an add-on guiding system seem unnecessary. When procedures must be done minimally invasively, however, electromagnetic guidance becomes essential. The addition of image guidance reduced the average task of one seed insertion by 60 s. For the robotic procedure, the average time was reduced by 30 s. The time saved becomes even more significant when more seeds need to be inserted.

Dosimetry planning was assessed using the Theraplan Plus software and has been found feasible [43]. In an effort to realize real-time dosimetry replanning as brachytherapy seeds are deposited, preliminary software has been developed by Dr. A. Fenster’s research team. The software accounts for actual seed position and recalculates the dosimetry as more seeds are deposited (Fig. 4.6). Further work is required to adapt the software for lung brachytherapy.
Limitations and Future Directions

Our system shows promise for improving minimally invasive brachytherapy procedures; however, there are also limitations that need to be overcome before clinical use. Due to the length and flexibility of the brachytherapy needles, the electromagnetic sensor needs to be located near the area of interest, that is, the tip of the needle. For our experiments, a customized needle was developed with the sensor manually attached near the tip of needle. The added bulk at the needle tip increases trauma to the lung tissue with every insertion. Furthermore, frequent needle changes (which might be needed in clinical scenarios) are impractical because the attachment and calibration processes are time-consuming. It is desirable to have either a disposable needle with a built-in sensor at the tip or an injector with a magazine for multiple seeds such as the Mick Applicator [54].

Fig. 4.6. Image of a dosimetry plan for brachytherapy using 3D US imaging. (Courtesy of Dr. Aaron Fenster)
A major limitation to any electromagnetic tracking system is the possible distortion in the field by magnetic interference caused by the presence of nearby metal objects. Improvements in technology have made the current generation of sensors less susceptible to such interferences. Our experience was that modest amounts of surgical steel in the environment do not cause any noticeable deterioration of accuracy. However, it would still be important to keep the amount of metal to a minimum, and the addition of metallic shields could ensure optimal performance.

The accuracy of brachytherapy seed injection was limited by the intrinsic resolution of the US probe. This resolution may be somewhat improved by using a newer probe or one with higher frequency (although this would have been at the expense of penetration depth). Three-dimensional US may hold the key to improved visualization and real-time dosimetry planning. A better sense of the tissue may be obtained through reconstruction of the 3D space by piecing together 2D images and their position information.

4.7 Conclusion

Advances in technology such as robotic assistance and image guidance give promise to improved performance of minimally invasive lung brachytherapy procedures, potentially expanding its clinical role and facilitating better patient outcome. Robotic assistance enables precise manipulation of the brachytherapy needle, while enhancing the ergonomics for the surgeon; real-time virtual reconstruction of the tissue of interest and image guidance allows more intuitive and reliable seed deposition. By integrating these two aspects of technology, the surgical procedure can be made more automatic, easier to learn, and less susceptible to user variability.

Summary

- Brachytherapy is becoming an option for both unresectable and early resected lung cancer.
- Three-dimensional US of lung tumors is feasible for dosimetry planning.
- Image-guided minimally invasive robotic-assisted brachytherapy is feasible for lung tumors.
References


5.1 Background

Laparoscopic Heller myotomy (LHM) has become the standard treatment option for achalasia. Evidence-based medicine has shown surgical treatment to be the most effective option due to the long-term improvement of symptoms following surgery [5, 6, 13, 20–23]. However, other treatment options are still practiced either due to unavailable surgical expertise or due to patient comorbidities, which prohibit general anesthesia. Recently, robotic-assisted Heller myotomy (RAHM) has been shown to be superior to LHM in terms of safety and comparable with LHM in outcome [14].

5.1.1 Etiology

Achalasia (failure to relax) is an esophageal disorder characterized by an impaired relaxation of the lower esophageal sphincter (LES) and ineffective peristalsis of the esophageal body [29]. Symptoms primarily consist of progressive dysphagia, odynophagia, and regurgitation. If untreated, the disease progresses to a dysfunctional dilated esophagus, which causes malnutrition, severe weight loss, and recurrent aspirations episodes, eventually leading to death. Achalasia is the most common primary motility disorder of the esophagus, but this disease is uncommon with an estimated annual incidence of about 1 in 100,000 individuals in North America [9]. The etiology is unknown, but studies suggest that the majority of patients have no ganglion cells of the myenteric plexus of Auerbach with a loss of postganglionic inhibitory neurons [10]. Hereditary, degenerative, autoimmune, and infectious factors are possible causes – the latter two being the most commonly accepted [24].
5.1.2 Diagnosis

The diagnosis of achalasia is based on the patient’s symptoms, barium swallow test, upper endoscopy, and esophageal manometry. A typical barium swallow study demonstrates esophageal dilation and delayed esophageal emptying, together with tapering of the esophagus at the level of the gastro-esophageal junction (bird’s-beak appearance). Upper endoscopy has a significant role in the process of diagnosis. It can confirm the findings of the barium swallow study but more importantly has a role in excluding mechanical obstruction caused by tumors and hence leading to pseudoachalasia [19]. Esophageal manometry determines the resting pressure and the inability of the LES to relax during swallowing. This study not only establishes the diagnosis of achalasia but also helps to exclude other motility disorders of the esophagus. The classic manometric findings include aperistalsis (identical simultaneous contractions) in the body of the esophagus and elevated resting pressure and failure of relaxation of the LES. Although in up to 50% of patients the LES resting pressure can be normal (10–45 mmHg), it is never low [24]. All achalasia patients have abnormal LES relaxation. About 70–80% of patients have absent or incomplete relaxation with wet swallows. The rest are complete relaxations but are of short duration (less than 6 s) and functionally inadequate. Failure to relax more than 50% or less than 10 mmHg remains the defining manometric characteristic of achalasia.

5.1.3 Treatment

The treatment of achalasia has largely evolved over the years. No treatment can restore muscular activity to the denervated esophagus in achalasia. Aperistalsis and impaired LES relaxation are not reversed, and the target is always palliative to decrease the outflow obstruction at the level of the LES. Several modalities were used in the past to address this disease: medical management, mechanical dilatation, chemical paralysis, and surgical myotomy.

5.1.3.1 Mechanical Dilatation

The first patient treated for achalasia was reported more than 300 years ago by Thomas Willis [34], who treated his patient by dilation of the lower esophagus with a sponge attached to a whalebone. The more controlled pneumatic dilatation replaced this mechanical way of treatment and till recently has been the first line of treatment due to the outpatient procedure, with initial success
rates of 65–80% [27]. However, the complication rates of esophageal perforation (2.6–15%), development of abnormal gastro-esophageal reflux (23–35%), and the need for repeated dilatations in up to 60% of patients kept this line of treatment from ever achieving gold standard status [29, 33].

5.1.3.2 Medical Management

This line of therapy targets to induce LES relaxation. Pharmacotherapy includes calcium channel blockers, long-acting nitrates, adrenergic β2-receptor agonist, anticholinergics, and phosphodiesterase inhibitors [28].

Reported results of medical management vary widely. Prospective, randomized controlled studies, [31] however, showed reduction in the LES pressure, but, unfortunately, the treated group still reported dysphagia, and the LES pressure was only about half the typical response from balloon dilation or surgical esophagomyotomy. Therefore, the authors of these studies concluded that medical management cannot be recommended as a standard alternative for treatment.

5.1.3.3 Chemical Paralysis

Currently, this line of treatment is limited to the use by a single agent, the neurotoxin of Clostridium botulinum. Botulinum toxin is a peptide that blocks the presynaptic release of acetylcholine. When injected endoscopically into the LES, the result is a reversible paralysis of the injected muscle. Clinically, there is an improvement of symptoms in almost 90% of patients. Unfortunately, the effect of this agent is mostly temporary and hence the need for repeated injections, which harbor decreased effectiveness and compromise of a more definitive therapy. Injection of botulinum toxin has been shown to increase significantly the technical difficulties and thus the potential risk of esophagomyotomy [13]. This line of treatment, therefore, is best reserved for high-risk surgical patients or those with high risk of perforation during pneumatic dilatation.

5.1.3.4 Surgical Esophagomyotomy

In 1913, Heller [11] performed the first esophagomyotomy using both anterior and posterior esophageal myotomy. This approach resulted in excessive gastro-esophageal reflux and was later modified to involve a single anterior myotomy, which is still the mainstay of the surgical treatment today.
5.1.4
Laparoscopic Heller Myotomy

In the early 1990s, Pellegrini et al. and Shimi et al. described the LHM. This technique showed the obvious benefits of minimally invasive surgery (MIS) including reduced morbidity, shorter postoperative hospital stay, and decreased postoperative pain [23, 26]; shortly afterward the LHM with a Dor fundoplication [3] has become the standard treatment option for achalasia. The high success rate of this approach caused a shift in the treatment algorithm for achalasia, and surgery has become the preferred treatment for this disease [22]. Although LHM is the most beneficial approach to the treatment of achalasia, this approach is a technically demanding operation, associated with a considerable learning curve [2]. A significant aspect of this operation is to achieve an adequate myotomy of the lower esophagus extending 1.5–2 cm into the gastric wall. Having an insufficient length of myotomy at the distal end of the esophagus may lead to persistent dysphagia. Extending the myotomy into the stomach is the most difficult part of the operation. The conversion of the muscle layers and their direction from circular at the esophagus to oblique at the stomach makes it difficult to maintain the same submucosal plane for division of the muscle fibers. It is at this site that bleeding is more likely and most mucosal perforations occur.

The rate of esophageal perforation during LHM (5–10%) remains nearly as high as those seen with the open techniques [9]. This complication may be due to the well-known pitfalls of laparoscopic surgery. Operating while the operative field view is unstable, using straight laparoscopic instruments with limited degrees of freedom, and having a two-dimensional vision of a three-dimensional environment are the drawbacks of this operative technique.

5.1.5
Robotically Assisted Heller Myotomy

The introduction of the RAHM approach in the early 2000s was the initiation point for better performances in several MIS procedures. The addition of three-dimensional vision, the suppression of the tremor, and the freedom of movement of the articulated instruments offered by the da Vinci Surgical System (Intuitive Surgical, Palo Alto, Calif.) facilitate the performance of operations that require a higher degree of skills like Heller myotomy. Robotically assisted surgery enables the precise dissection of the gastro-esophageal junction by offering a clear view of the submucosal plane, a better angle of approach to the muscle fibers, and reduction of the surgeon’s tremor, thereby reducing the risk of mucosal perforation [14].
5.2 Surgical Technique

The following description is the technique described earlier by Horgan et al. [4, 14].

The diagnosis of achalasia in the preoperative evaluation period was based on symptoms, barium swallow, upper endoscopy, and esophageal manometry.

Following general anesthesia, the patient is placed in the semilithotomy position over a bean bag. The room set-up is shown in Fig. 5.1.

Fig. 5.1. The robotic system has three major components: the surgeons’ console, the robotic arms, and the control tower. The OR setup illustrated allows for best communication among the OR staff.
5.2.1
Heller Myotomy

For this procedure five ports are used. The camera port (12-mm trocar) is placed 2 cm to the left of the umbilicus, approximately two fingerbreadths above the umbilicus. Two 8-mm trocars are placed in the right and left upper quadrant in the midclavicular line for the two robotic arms. A 5-mm port is placed in the subxyphoid area for anterior retraction of the left liver lobe, using the Nathanson liver retractor. An assistant port is placed in the left anterior axillary line 2 cm below the costal margin (Fig. 5.2). Following the achievement of pneumoperitoneum, the nursing personnel approximate the robotic surgical cart into position, and the arms of the robot are attached to the camera port and two working 8-mm ports.

The operation is started by dissecting the left and right crura and dividing the proximal short gastric vessels using the harmonic scalpel. Only the anterior part of the esophagus is dissected, respecting the posterior attachments. In order to expose the gastro-esophageal junction, the fat pad is removed after the

![Image](Image.png)
insertion of a 44-French bougie to distend the lower esophagus. The anterior branch of the vagus nerve is mobilized from the esophageal wall and retracted laterally. The myotomy is started out just above the gastro-esophageal junction on the 12 o’clock position, using the robotic articulated hook electrocautery (Fig. 5.3). Once the submucosal plane is exposed, it is followed proximally and distally to extend the myotomy for a minimum of 6 cm proximally and 2–3 cm distally into the stomach.

### 5.2.2 Antireflux Procedure

The preferred antireflux operation is the Dor fundoplication, which is an anterior 180° fundoplication [8]. This type of fundoplication is composed of two rows of sutures. The first stitch on the left side includes the gastric fundus, the left crura, and the left side of the myotomy. The remaining two stitches on that side do not include the crura (Fig. 5.4). The second row of sutures is created in the same fashion but incorporates the gastric fundus lateral to the first row of sutures. The first stitch on the right side incorporates the gastric fundus, the right crura, and the right side of the myotomy. The remaining two stitches

![Fig. 5.3. The articulating robotic hook is dissecting and dividing a single strand of esophageal muscle fiber](image)
are then placed between the stomach and the right edge of the myotomy not including the crura.

At the time of completion of the RAHM, there is an 8-cm myotomy (6 cm on the distal esophagus and 2 cm on the stomach) covered by the gastric fundus, which serves as the antireflux mechanism.

5.3 Global Experience

Achalasia is an uncommon disease, with an annual incidence of about 1 in 100,000 individuals in the United States. Due to the necessary expertise for surgical treatment, only large referral centers end up operating on these patients. RAHM was introduced in the early 2000 and is performed only within those centers that have a robotic-assisted surgery program as well. Therefore, the reported experience of this approach is modest. Only seven institutions have reported their experience in RAHM to date (Table 5.1), with the largest single institution series being of 59 patients [9]. In an effort to increase statistical power and evidence, multicenter studies and author collaboration resulted in the larg-

**Fig. 5.4.** Performing the antireflux procedure following a complete myotomy. The third suture of the left row of a Dor fundoplication is being placed
<table>
<thead>
<tr>
<th>Group</th>
<th>No. of patients</th>
<th>Antireflux procedure</th>
<th>Mean operation time (min)</th>
<th>Mucosal perforations</th>
<th>Year reported</th>
<th>Mean length of stay (days)</th>
<th>Follow-up (months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ayav et al. 2004 [1]</td>
<td>2</td>
<td>Dor</td>
<td>145</td>
<td>0</td>
<td>2004</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>Talamini et al. 2002 [30]</td>
<td>5</td>
<td>Dor</td>
<td>218</td>
<td>0</td>
<td>2002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horgan and Vanuno 2001 [12]</td>
<td>9</td>
<td>Dor</td>
<td>140</td>
<td>0</td>
<td>2001</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Melvin et al. 2002 [17]</td>
<td>9</td>
<td>Dor</td>
<td>140</td>
<td>0</td>
<td>2002</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Undre et al. 2004 [32]</td>
<td>5</td>
<td>None</td>
<td>115</td>
<td>1</td>
<td>2004</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Galvani et al. 2006 [9]</td>
<td>54</td>
<td>Dor</td>
<td>162</td>
<td>0</td>
<td>2006</td>
<td>1.5</td>
<td>17</td>
</tr>
<tr>
<td>Horgan et al. 2005 [14]</td>
<td>59</td>
<td>Dor</td>
<td>141</td>
<td>0</td>
<td>2005</td>
<td>1.5</td>
<td>18</td>
</tr>
<tr>
<td>Melvin et al. 2005 [18]</td>
<td>104</td>
<td>Dor</td>
<td>140</td>
<td>0</td>
<td>2005</td>
<td>1.5</td>
<td>16</td>
</tr>
<tr>
<td>Iqbal et al. 2006 [15]</td>
<td>19</td>
<td>Dor</td>
<td>0</td>
<td>2006</td>
<td>12 (median)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
est multicenter study of 104 patients [18]. Although some of the patients listed in Table 5.1 overlap, the most evident feature is the single mucosal perforation that occurred in about 154 patients. The procedure times vary due to the lack of clear definition of procedure time, but in the larger series the operative time is between 140 and 162 min, with the clear demonstration of improvement in time with experience. In the largest single-institution series, Horgan [14] states that the operative time, including the robotic setup time, decreased from an average of 162 to 90 min in the last 10 patients. The postoperative complication rate and the mean length of stay were comparable to LHM in each institution.

5.4 Discussion

Achalasia is the most common primary motility disorder of the esophagus. It is however uncommon with the estimated annual incidence of 1 in 100,000 individuals in the United States [9]. The treatment of achalasia has always aimed to decrease the outflow obstruction at the level of the LES and improve esophageal emptying. Up until about a decade ago, the first line of treatment was pneumatic dilatation. Although this is an outpatient procedure, it has an initial success rate of 65–80% and furthermore an esophageal perforation rate of 2.6–15% and a development of an abnormal gastro-esophageal reflux rate of 23–35%. Up to 60% of the patients need repeated dilatations.

Transabdominal anterior esophageal myotomy was shown in the 1980s to offer long-lasting results in 90–95% of patients [5, 6]. The drawbacks of general anesthesia, hospital stay, morbidity, and mortality were overcome with the introduction of MIS. Since the advent of the LHM, it became clear that this approach offers a superior long-term success rate and a decreased perforation rate. Together with the obvious advantages of MIS, which include less postoperative pain, shorter hospital stay, shorter disability, lower cost, and excellent cosmetic results [21], this approach shifted the treatment algorithm of achalasia. LHM has become the first line of treatment whenever surgical expertise is available. The addition of a partial fundoplication is still controversial but is intended to prevent the occurrence of gastro-esophageal reflux after the obliteration of the LES in this procedure. Although LHM was shown to be beneficial to any other treatment, it is a technically challenging operation, and expertise is required for assuring the success of this approach. The two-dimensional image of a three-dimensional environment, the unstable camera view, and the limited ability of instrument manipulation contribute to the comparable mucosal perforation rate of LHM to open surgery – as high as 16% [14]. RAHM, however, has the advantage of a three-dimensional vision, a stable camera, and articulated instruments with seven degrees of freedom. These capabilities, together with the
ability to ablate the surgeon’s tremor and to downscale the surgeon’s motions – the most difficult part of the operation being the extension of the esophagomyotomy into the stomach – are significantly facilitated and they optimize the operative outcome. Although RAHM is practiced only for 6 years, it was shown to be a safe procedure with comparable outcome to LHM and superior results in terms of mucosal perforation. RAHM, as shown here, has only a 0.6% rate of mucosal perforation, and this single perforation in 154 patients occurred within the first five patients of one of the published series (Table 5.1).

In order to obtain optimal results while performing RAHM, it is imperative to adhere to the technical principles of Heller myotomy. One should obtain a complete mobilization of the fundus of the stomach by dividing the short gastric vessels, perform an adequate extension of the myotomy (6 cm into the distal esophagus and 2–3 cm into the stomach), and add a partial fundoplication.

Educating surgical residents and fellows to perform RAHM is a challenge by itself. Teaching to perform LHM seems to be easier and safer, due to the ability of the mentor to better control the operating instruments. Having the trainee in the operating console and the mentor beside the patient diminishes the necessary interaction between the two and seems to be the weakness of this approach. In order to reduce the risk of inexperience, a second robotic system must be available, either for preoperative training and simulations of surgery or for enabling the mentor to take control and demonstrate the necessary movements during the operation in a master-slave console fashion.

We believe that in the future referral centers will gain the necessary expertise and will develop specialized teams for specific procedures like RAHM for achalasia. These specialized teams will be available for telementoring and telesurgery in any institution, with the capabilities for live teleconference and/or telesurgery. The robotic systems of today already allow this expertise gained to be available worldwide. Internet and/or satellite connection enable telementoring [7] and telesurgery [16] overseas. The acceptable time delay, between the surgeon’s console and the robotic laparoscopic image, in order to reduce the operator error to a minimum, was shown to be 330–700 ms [16]. Transcontinental delays of 1.4–12 s have been observed in satellite telesurgical connections [7], but connection via ATM (asynchronous transfer mode) technology enables a delay of only 155 ms. Currently, such connections are not widely spread, but hopefully in the near future even hospitals in rural areas will have the capability to connect robotic arms to a surgeon’s console located in one of the highly specialized referral centers.
Summary

- LHM has become the standard treatment option for achalasia.
- RAHM is superior to LHM due to the capability for precise dissection, reduction of the surgeon's tremor, and a better angle of approach to the esophageal muscle fibers.
- Telesurgery via fast Internet connections will enable rural hospitals to benefit from highly experienced surgeons in their field of expertise.

References

Robotic-Assisted Surgery: Low-Cost Options

JENS RASSWEILER, ALI S. GOEZEN, WALTER SCHEITLIN, DOGU TEBER, and THOMAS FREDE

6.1 Introduction

Open surgery is based on the access to the treated organ via one large 5- to 30-cm incision dividing the skin and abdominal muscles or fascias. This large skin incision provides the surgeon and assistant(s) with a direct view of the anatomy, enabling the introduction of their hands and instruments. They can look down at their work with their heads and necks in a neutral position, using both hands, with natural hand-eye coordination (Fig. 6.1a). For delicate surgical actions, it is even possible to support the wrists by leaning on the patient’s body or on a specially developed armrest [7, 21, 33]. However, there are also some drawbacks, particularly in case of pelvic surgery:

- The light conditions might be suboptimal.
- The distance to the tissue/organ is relatively long (i.e., urethra).
- The view to the object might be hindered by bone (suprapubic spine).
- The view for the assistant might be suboptimal due to the narrow anatomical conditions.
- The position of the surgeon is ergonomically suboptimal (i.e., torsion of the body).

Therefore, in open surgery, surgeons started to work with headlights and magnifying loops (Fig. 6.2) or used digital systems for high definition (HDTV, Olympus-IBE, Hamburg, Germany). Recently, an external magnifying camera system has been introduced [44].

Endoscopic surgery represents an operating technique based on the access to the tissue via several small skin incisions, ranging from 3 to 15 mm. One incision is used for insertion into an endoscope. The surgeon and assistant(s) look at a monitor on which the endoscopic images are displayed (Fig. 6.1b). To create a sufficient working space inside the patient, the cavity (peritoneum and retroperitoneum) is insufflated with carbon dioxide. To prevent leakage of the gas and to protect the tissue near the incision, the instruments are inserted...
through trocars or ports with an airtight sealing. The advantages of these small incisions are the minimized access trauma with reduced postoperative pain, less blood loss, shorter hospital stay, improved cosmetics, and reduced risk of wound infection. Additionally, laparoscopy is able to overcome some of the drawbacks of open surgery [10, 13, 26, 35, 41, 42] by:

- Providing good light conditions at the working space
- Enabling optimal view to the treated tissue/organ
- Providing magnification of the anatomical details
- Offering the same image to surgeon and assistant(s)

However, there are also some distinct disadvantages of endoscopic surgery, which have constantly blocked the diffusion of this novel surgical technique (Table 6.1).

---

**Fig. 6.1.** Comparison of working ergonomy during radical prostatectomy. a Open surgery: OR field in line with the eyes and hands, but note the torsion of the body and deflection of the neck. Standing surgeon and assistant may not have the same view; OR staff has no view to the OR field. b Laparoscopic surgery (standard): standing surgeon, assistant, and OR staff have the same view on the monitor. However, working axis/field is not in line with the eyes and hands. c Robotic surgery: surgeon sits at the console with eyes and hands in line with the virtual OR field. Control of coagulation and camera by foot pedal. Assistant and nurse have view on 2D screen, with limitation of movements due to the manipulators. d Laparoscopy with ergonomic seat for surgeon

**Fig. 6.2.** High-definition 3D microscopic system, with polarized glasses for laparoscopy (True Vision). Assistant and OR staff have the magnified view but need to wear glasses.
### Table 6.1. Overview of the qualities of open, laparoscopic, and robot-assisted surgery (da Vinci) during pelvic surgery (i.e., radical prostatectomy)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Open surgery</th>
<th>Laparoscopy</th>
<th>Robot assisted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working ergonomy</td>
<td>Impaired</td>
<td>(Slightly) impaired</td>
<td>Optimal</td>
</tr>
<tr>
<td>Position of surgeon</td>
<td>Standing with rotation, no armrest</td>
<td>Standing with rotation, sitting optional</td>
<td>Sitting with armrest, no rotation</td>
</tr>
<tr>
<td>Activation of energy sources</td>
<td>Hand piece (HF generator) or by assistant</td>
<td>Foot pedal (cave: standing)</td>
<td>Foot pedal (sitting)</td>
</tr>
<tr>
<td>Quality of vision</td>
<td>Impaired</td>
<td>(Slightly) impaired</td>
<td>Optimal</td>
</tr>
<tr>
<td>Illumination</td>
<td>Inhomogeneous (OR light); headlight optional</td>
<td>Xenon light (at telescope)</td>
<td>Xenon light (at telescope)</td>
</tr>
<tr>
<td>Magnification</td>
<td>None; loops (2.5-fold);</td>
<td>5- to 8-fold</td>
<td>Up to 10-fold</td>
</tr>
<tr>
<td>Image</td>
<td>3D</td>
<td>2D, 3D helmet</td>
<td>3D</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>Slightly impaired</td>
<td>Impaired</td>
<td>Impaired</td>
</tr>
<tr>
<td>Eye-hand coordination</td>
<td>Inline</td>
<td>Offline</td>
<td>Inline</td>
</tr>
<tr>
<td>Tactile feedback</td>
<td>Optimal</td>
<td>Reduced</td>
<td>None</td>
</tr>
<tr>
<td>Angle of instrument</td>
<td>Free</td>
<td>Fixed</td>
<td>Fixed/clutch</td>
</tr>
<tr>
<td>Degree of freedom (DOF)</td>
<td>4 DOF (but no fixation)</td>
<td>4 DOF</td>
<td>6 DOF</td>
</tr>
<tr>
<td>Length of instrument</td>
<td>Variable</td>
<td>Long</td>
<td>Long</td>
</tr>
<tr>
<td>Handle</td>
<td>Scissor-like palm handle</td>
<td>Scissor-like palm handle</td>
<td>Two loops</td>
</tr>
</tbody>
</table>
Table 6.2. Definition of DOF and copying mechanisms in mechanical and robotic manipulators

<table>
<thead>
<tr>
<th>DOF</th>
<th>Description</th>
<th>Copying mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>Rotations about the incision (pitch, jaw)</td>
<td>Parallelogram</td>
</tr>
<tr>
<td>3</td>
<td>Rotation about the instrument axis (rotation)</td>
<td>Steel wire</td>
</tr>
<tr>
<td>4</td>
<td>Translation along instrument axis (insertion, extraction)</td>
<td>Steel wire</td>
</tr>
<tr>
<td>5, 6</td>
<td>Deflection of instrument tip (pitch, jaw)</td>
<td>Steel wire</td>
</tr>
<tr>
<td>7</td>
<td>Opening of instrument tip (actuation)</td>
<td>Steel wire</td>
</tr>
</tbody>
</table>

6.2 Problems of Endoscopic Surgery

6.2.1 Disturbed Hand-Eye Coordination

One difficulty is that the coupling between perception and manipulation, the hand-eye coordination, is disturbed. In open surgery, coordination of hand movements is based on direct view of the hands and the tissue to which the brain has been trained from childhood onward. In endoscopic surgery, the monitor is usually not positioned in the surgeon’s natural line of sight, but on a cart next to the patient, so that the surgeon has to look up respectively to the side (Fig. 6.1b). In addition, the endoscope may have a line of sight different from the line of sight of the surgeon’s eyes [7, 21].

6.2.2 Limited Range of Motion

Laparoscopic surgery is handicapped by the reduction of range of motion because of the fixed trocar position determining the angle of the respective instrument to the working field. The incision point acts like a spherical joint that reduces the degrees of freedom (DOF) of the instrument from six to only four, plus the actuation of instrument (Table 6.2).
6.2.3 Limited Spherical Vision

Another problem is the two-dimensional (2D) view of the telescope. The absence of shadows, stereovision, and movement parallax in particular, makes it difficult for a surgeon to accurately determine spatial distance and movements. The latter may be compensated for, if the working field is small and the camera is close to the object [41].

6.3 Solutions for Endoscopic Surgery

6.3.1 Geometry of Laparoscopy

Some of the problems with the availability of only four DOF might be compensated for, if important geometrical factors influencing laparoscopic surgery are adequately taken into consideration (Table 6.3) [13, 14].

Concerning the angle between the instruments, the operative step is important. In case of dissection, the angle between the instruments can be in the range 15–25°. For endoscopic suturing (Fig. 6.3), however, the angle should...
be between 25 and 45°. This needs to be considered when planning the trocar placement.

Moreover, the angle between the instruments and the horizontal line of the working plane is important. During open procedures, the surgeon automati-
cally chooses a flat angle, if possible. The same applies to microsurgery, where the surgeon works with the support of the forearms. In case of laparoscopy, the angle should be less than $55^\circ$. If the individual anatomy does not allow adequate placement of the trocars, then the patient has to be turned toward the surgeon to reduce the angle with respect to the horizontal line.

Laparoscopic suturing may also become cumbersome due to an inadequate working height of the surgeon. Often, the distance to the trocars is too small, which is compensated for by lifting the surgeon’s shoulders. In an ergonomically relaxed position, the surgeon needs to work with orthogonally deflected elbows. For this purpose, the operating table has to be adjusted according to the size of the surgeon (Fig. 6.1b).

6.3.2 Working Ergonomics of Laparoscopy

Even if all geometrical aspects are taken into consideration, for most laparoscopic procedures, the working position of the surgeon is not ergonomic. Moreover, the additional use of foot pedals for control of energy sources, together with the rotation of the standing surgeon, may lead to non-physiologic pressure on the knee. Accordingly, several laparoscopic pioneers are suffering from knee problems. One solution might be to perform at least major parts of the procedure in a sitting position (Fig. 6.1d). Another option might be the design of the instruments with fingertip or palm activation of the energy sources (Fig. 6.4b).

6.3.3 Adjustment of Needle and Needle Holder

Since, during endoscopic suturing, the exposure of the tissues to be sutured together might not be ideal, the angle between the needle and the shaft of the needle holder gains importance. The modification of the two angles compensates for the loss of two DOF (i.e., jaw and pitch of the tip of the instrument; Table 6.2). If the stitch is orthogonal to the tissue, then it requires a $90^\circ$ angle between the shaft and the needle, similar to the open technique. For difficult sutures with oblique direction of the stitch (i.e., urethrovesical anastomosis), the position of the needle has to be adjusted according to the anatomy of the patient (Fig. 6.3a). The needle should pass through the tissue only by rotation of the needle holder. Usually, the biplanar angle between the needle and the shaft is in the range of 100 to 120°, on both planes. Such tricks have to be used also in open surgery, because the needle holder cannot be angled at the tip. Only 6-DOF instruments provide almost unlimited maneuverability [14].
6.3.4 Instruments with Six Degrees of Freedom

Some manufacturers tried to increase the DOF of endoscopic instruments by addition of deflection [4, 19]. We have significant experience with a new mechanical device, the Radius Surgical System (Tübingen Scientific, Tübingen, Germany). The system consists of two hand-guided mechanical manipulators, which allow multiple DOF based on a deflectable and rotatable tip of the instrument (Fig. 6.3b). Similar to robotic systems, different interchangeable surgical end-effectors are available and can be connected to the tip of the instrument. Experimental and clinical experience proved to be very promising. Like with...
The advantages of the Radius system include the increased DOF with deflection and rotation of the instrument. Additionally, the system is cost-effective and can be used almost similar to a standard endoscopic instrument (i.e., autoclavable). However, the needle grip and fixation of the filament need improve-
ment. The size of the instrument is limited to 10 mm, and, of course, further instrument tips (end-effectors) should be developed (i.e., Metzenbaum scissors, etc.), including the use of mono- or bipolar HF current.

### 6.3.5 Stereovision

A number of aids have been described to improve the surgeon’s depth perception [41]. Stereovision can be accomplished by using a stereo-endoscopic system [19]. Earlier systems used two 5-mm lenses in one telescope, creating a double image on the video monitor, which was unified to a three-dimensional (3D) picture by use of shutter glasses. Problems included the fact that only the surgeon had a normal endoscopic picture, whereas the assisting nurses and the anesthesiologist had to view the double image on the screen [15].

We tested a 3D system (Karl Storz, Tuttlingen, Germany) taking two images with one telescope from different angles. The image is digitally reconstructed. If the surgeon wears polarized glasses quite similar to sunglasses, he or she gets a 3D image, whereas without glasses the picture on the screen is normal. The handling was much more convenient for the assisting surgeon and nurse. However, the image on the screen significantly loses brightness and resolution, compared to the three-chip CCD camera [36].

A further development of 3D systems represents the fusion of two images on a screen of a helmet, as realized by Viking or Vista. Since both the surgeon and the assistant can be equipped with a helmet, and the staff can watch the procedure through one of the two images, the earlier drawbacks do not exist anymore. However, the resolution and clarity of the picture are still inferior compared with the 2D image of a CCD camera or the stereovision provided by the da Vinci robot.

Comparisons between mono- and stereo-endoscopes have demonstrated that 3D systems show no advantages for the experienced surgeon [31], because the loss of stereovision can be well compensated by magnification, brightness, and sharpness of the new three-chip cameras, together with the experience of the laparoscopic surgeon. This effect may be even more dramatic with the newly introduced HDTV technology.

### 6.3.6 Robotic Camera Holders

Principally, there are two basic approaches for the mechanism of camera holder design: (1) a selective compliance assembly robot arm type (SCARA), consisting of three motorized joints in combination with one passive (ball) joint, the three DOF being indirectly translated to the three different DOF, and
(2) a parallelogram type, consisting of three motorized joints that directly activate the three DOF of the scope [6, 21, 22, 24].

Actually, two robotic camera holders are commercially available [2, 25, 32, 45]: the EndoAssist (Prosurgics, London, UK), which uses the head movements of the surgeon to activate the camera arm (Fig. 6.4a), and the LapMan (Medsys, Gembloux, Belgium), which uses control buttons in the surgeon’s hand and has recently become connectable to the handle of an endoscopic instrument (LapStick; Fig. 6.4b).

Most clinical experience exists with the automated endoscopic system for optimal positioning (AESOP, Intuitive Surgical, Sunnyvale, Calif.), which enables the surgeon to move the telescope by pre-programmed and individually recorded demands (SCARA type; Fig. 6.4c). Every surgeon has his/her own voice disk that allows him/her to use any AESOP worldwide [2, 24, 36]. The device alone enables solo surgery (i.e., radical nephrectomy and pyeloplasty), or, in the case of radical prostatectomy, the operation can be performed by two surgeons (Fig. 6.1b) or, as demonstrated by Antiphone [3], even alone. AESOP is the first robotic device that was used for transatlantic telementoring [20]. Unfortunately, due to the takeover of Computer Motion by Intuitive Surgical, AESOP will no longer be manufactured.

Buess et al. [8] developed a remote-controlled camera arm (FIPS-endo-arm). Like the AESOP, the system is driven by means of a speaker-independent voice control or a finger-ring joystick.

The basic idea behind these active holders is that the surgeon does not have to interrupt the surgical process, and that it becomes unnecessary to release an instrument for repositioning of the camera. Interestingly, with increasing experience, the control of the camera holder without any hand (i.e., by voice) becomes less important. However, at least the arm should be movable with a single hand (Table 6.4).

6.3.7 Passive Holders for Camera and Instruments

Recently, mechanical camera arms, powered by high-pressure air (i.e., Uni-track, Aesculap, Tuttlingen, Germany; Endoboy, Endobloc, France), have been introduced as a cost-effective alternative [11, 40]. Other mechanical holders, consisting of a number of bars connected with joints, have been initially designed for open surgery (i.e., Martin’s Arm retractor; Fig. 6.4d) and modified for laparoscopy (Karl Storz). These holders can be attached to the operating table, and their tips contain a clamp that holds the endoscope or an additional instrument [22]. Of course, such devices do not provide any robotic features, such as pre-programmed positioning, voice-controlled movements, and tele-
Table 6.4. Overview of passive and active camera holders

<table>
<thead>
<tr>
<th>Device</th>
<th>Joint control</th>
<th>Break release</th>
<th>Hands for reposition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Passive holders</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Martin’s Arm (Karl Storz)</td>
<td>Mechanical (knob)</td>
<td>Manually</td>
<td>2</td>
</tr>
<tr>
<td>Assisto (Geomed)</td>
<td>Mechanical (knob)</td>
<td>Manually</td>
<td>2</td>
</tr>
<tr>
<td>Unitrack (Aesculap)</td>
<td>Pneumatic</td>
<td>Manually</td>
<td>1</td>
</tr>
<tr>
<td>First Assist (Leonard Medical)</td>
<td>Pneumatic</td>
<td>Manually</td>
<td>1</td>
</tr>
<tr>
<td>Endoboy (Endobloc)</td>
<td>Pneumatic</td>
<td>Manually</td>
<td>1</td>
</tr>
<tr>
<td>TISKA (Karlsruhe Research)</td>
<td>Electro-mechanical</td>
<td>Foot pedal</td>
<td>1</td>
</tr>
<tr>
<td>PASSIST(AMC)</td>
<td>Spring balanced</td>
<td>Manually</td>
<td>1</td>
</tr>
<tr>
<td><strong>Active holders</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AESOP (Intuitive Surgical)</td>
<td>Electric motors</td>
<td>Voice, manually</td>
<td>0/1</td>
</tr>
<tr>
<td>EndoAssist (Prosurgics)</td>
<td>Electric motors</td>
<td>Head, manually</td>
<td>0/1</td>
</tr>
<tr>
<td>LapMan (Medsys)</td>
<td>Electric motors</td>
<td>Joystick (LapStick)</td>
<td>1</td>
</tr>
</tbody>
</table>

mentoring. According to their design, they require one or two hands for manipulation (Table 6.4).

6.3.8 Master-Slave Systems

Master-slave devices are used in nuclear research and industry. In medicine, such systems have been developed to perform open trauma surgery in the battlefield, with the surgeon controlling the manipulators from a distant and safe location [17, 38]. None of such devices are real robots but represent operator-controlled manipulators (Table 6.5).
In 1994, Schurr et al. [39] developed the ARTEMIS system and presented their first experimental results, after successfully performing a telesurgical laparoscopic cholecystectomy on swine. ARTEMIS consisted of the user station (master) and the instruments station (slave).

In 2000, Birkett [5] presented another telesurgery system (Laprotek, Brock-Rogers, Boston, Mass.). The instruments provide all six DOF and – similar to the da Vinci Surgical System – they are moved by mini-motors mounted on both sides of the operating table. The control of the end-effectors is realized by use of electronic data gloves, transmitting the movements of the finger and ankle movements.

### 6.3.8.2
**Clinically Used Robotic Manipulators**

The ZEUS system (Computer Motion, Goleta, Calif.) was based on the combination of a control unit and a telemanipulator. The manipulator consists of three separate robot arms transported on small carts. Two arms control the 4-mm instruments; the third arm consists of the AESOP camera holder. The sur-
geon is seated in a high-backed chair with armrests, handling the instrument controllers. The camera is positioned by voice control. A 2D video endoscopic camera provided operating-field visualization. For 3D vision, the ZEUS system could be combined with a head-mounted system (i.e., VISTA). This system provided only four DOF. In conclusion, surgery has become even more difficult, as reflected in longer OR times [18, 28, 37]. A most spectacular event represented the “Lindbergh operation” when performing the first telesurgical laparoscopic cholecystectomy, with surgeon being in New York and the patient in Strasbourg, using the ZEUS system [29]. The transmission delay was about 150 ms, over a distance of more than 15,000 km, using very expensive fiber optics. Since the takeover of Computer Motion by Intuitive, the device is no longer manufactured.

The da Vinci Surgical System (Intuitive Surgical, Mountain View, Calif.) currently is the only existing robotic manipulator on the market [1, 30, 34]. The device has been designed with stereo-endoscopic system, a computer-controlled mechanical wrist providing six DOF (plus actuation of the instrument), used from a console with handles that can be utilized at the console always in an ergonomic working position (Fig. 6.1c). Two slave manipulators provide three DOEs (pitch, jaw, and insertion). The last elements are the surgical instruments or end-effectors: At the tip of the instruments, a cable-driven mechanical wrist adds three more DOF and one motion for tool actuation. The grip torque of the end-effector was programmed to 1 N. The video image gathered from inside the abdomen, provided by two three-chip cameras arranged in parallel, is so projected that it coincides with the workspace of the master manipulators. This overlap creates the visual illusion for the surgeon that his/her hands are holding onto tool tips inside the body (Fig. 6.3c). In addition, unintended movements caused by tremor are filtered. Finally, it is possible to temporarily disconnect the end-effectors from the master handles within its working space, while the position of the instruments remains unchanged (clutch function controlled by foot pedal). Recently, a third arm has been designed for retraction during surgery, reducing the work of the assistant.

6.3.8.3 Mechanical Manipulator

The minimally invasive manipulator (MIM), designed by Jaspers et al. [21, 23] and developed at the University of Amsterdam, represents a purely mechanical device for intuitive control of surgical instruments in six DOF. For copying of the movements of the first DOF (rotation about the incision), a parallelogram mechanism has been chosen (Fig. 6.5a), while the transfer of the movements in the other five DOF is provided by steel pre-loaded wires (Fig. 6.5b). In this prototype, the friction and elasticity for most DOF are low, when
Fig. 6.5. The minimally invasive manipulator (MIM), a mechanical manipulator. a The movements of the handle are transferred through parallelogram to the movements of the instrument tip (right). Moreover, a counterweight ($B_1, B_2$) is balancing the weight of the handle and the instrument of the manipulator. b Prototype design
compared with a conventional instrument. The friction for the translation movement should be reduced, and the stiffness of the wrist and grasping function should be increased (Table 6.6). An actuated approach with force sensors (i.e., like in the da Vinci system) was not used for this purpose, because it would have made the manipulator unnecessary complex and expensive. It should only be considered if mechanical solutions are not satisfactory. As surgical actions are executed in a precise and slow manner, the dynamic behavior of the manipulator is less important. Further experiments were performed with the MIM in combination with a 3D Cardio View Head-UP-Display (VISTA Medical Technologies, Carlsbad, Calif.) and a passive camera holder (PASSIST), showing a significantly lower failure rate in standardized pelvi-trainer experiments.

Activating the MIM is similar to activating a surgical robot; therefore, surgeons with experience in robotic surgery will be quicker to adapt to working with the manipulator than will an open surgeon or conventional laparoscopist. The MIM is a passive mechanical endoscopic instrument, with the same DOF as a robotic system (i.e., da Vinci), but with force feedback. When compared with conventional laparoscopic instruments, the MIM improves the ergonomics for the surgeon, enabling the surgeon to position his/her hands in a natural orientation to each other, providing improved eye-hand coordination, intuitive manipulation, and an ergonomic posture. There were still some technical flaws in the prototype: The handles could not be positioned favorably, which led to an additional amount of unnecessary failures, like dropping of the needle. The higher friction in DOF 4 (Table 6.6) made it harder to manipulate in a small

<table>
<thead>
<tr>
<th>DOF</th>
<th>Endoscopic instrument</th>
<th>Mechanical manipulator</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Friction</td>
<td>Stiffness</td>
</tr>
<tr>
<td>1</td>
<td>–</td>
<td>0.2 N/mm</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>0.2 N/mm</td>
</tr>
<tr>
<td>3</td>
<td>0.007 N m</td>
<td>2.6 N m/rad</td>
</tr>
<tr>
<td>4</td>
<td>1.2 N</td>
<td>200 N/mm</td>
</tr>
<tr>
<td>5</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>6</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>7</td>
<td>0.008 N m</td>
<td>22 N m/rad</td>
</tr>
</tbody>
</table>

*Weight 100–250 g; + weight 5.5 kg
range (i.e., fine movements), and the joints of the instruments are not protect-
ed, making it an easy trap for a piece of suture to get caught in.

6.4
Actual Boom of Robotic-Assisted Radical Prostatectomy

Initially, the *da Vinci* system was designed for heart surgery [12], but it has
become one of the most spectacular and useful devices, continuously replacing
open and also conventional laparoscopic radical prostatectomy. The main rea-
son lies in the fact that the device enabled experienced open surgeons to con-
vert relatively easily the *da Vinci* robot to the endoscopic technique [1, 30]. The
procedure consists of two parts – ablative and reconstructive – both performed
in a relatively small working field. Therefore, changes of the ports or position-
ing are not required. Another reason why the device was increasingly used by
many urological centers in the United States represents the patient’s require-
ment to be operated by the robot.

6.4.1
Disadvantages of the da Vinci Device

6.4.1.1
Lack of Tactile Feedback

Standard laparoscopy only provides a minimal amount of tactile sensation.
However, the effect of training and experience finally enabled the surgeon to
have a certain haptic sensation, i.e., to assess the shape of the prostate or the
strength of a suture. The *da Vinci* system, however, does not provide any tactile
feedback. The surgeon has to compensate for the missing tactile feedback by the
improved stereoscopic vision (i.e., observing the deformation of tissue and the
increasing tension on the suture). With increasing experience, it was possible
to estimate the applied strength on the suture when performing a knot. Never-
theless, working remotely without tactile feedback requires new surgical skills
solely based on visual inputs. A mechanical manipulator or 6-DOF instrument
enables similar tactile feedback qualities as laparoscopy.

6.4.1.2
Coordination with the Assistant

The complexity of radical prostatectomy itself requires proper assistance
and instrumentation. There is a need for retraction of the gland or adjacent
structures. Due to the relatively large size of the manipulator arms, the assis-
tants (i.e., surgeon and nurse) are significantly hindered in their movements. Moreover, the screen for the assisting staff still provides only 2D images (Fig. 6.1c). This might be compensated by the installation of a large 3D screen. A mechanical manipulator as well as any 6-DOF instrument can be used at the OR table, enabling the surgeon to have direct contact with the assistants and to even the use of their instruments if necessary.

6.4.1.3 Learning Curve

Several groups could demonstrate that for both laparoscopic-experienced and -inexperienced surgeons the learning curve of the device is short [1, 30]. Particularly, during operative steps requiring endoscopic suturing, the six DOF of the end-effectors (i.e., needle holder) proved to be very helpful. In their hands, the OR time could be reduced down to the level of open and laparoscopic surgery. However, one might speculate about the advances these teams would have made, had they continued the training program of standard laparoscopy. Recently, Frede et al. demonstrated the transferability of laparoscopic expertise at a center of expertise [15]. Early experience with 6-DOF instruments indicates that they also require a learning curve, but this is shorter for conventional laparoscopy.

6.4.1.4 High Investment and Running Costs

The most important reason for the limited distribution of the device in Europe is the high investment and running costs, which amount to actually about $1,400,000 and $100,000 per year, respectively [9]. This means that the cost per case might be increased by $2,000–2,500. With the actual reimbursement situation in Europe, only a few urologic centers will be able to afford this. All of the existing major laparoscopic centers in Europe have long waiting lists. This means that – unlike in the United States – the investment in a robotic device will not increase the number of patients, and therefore any advertising effect is questionable. Recently, Lotan et al. [27] presented a cost comparison of open, laparoscopic, and robot-assisted techniques using the results presented by centers of expertise. Open retropubic radical prostatectomy was the most cost-effective approach, with an advantage of $487 and $1,726 over laparoscopic (LRP) and robot-assisted prostatectomy (RAP), respectively.
6.5 Future Perspectives and Directions

The use of robots in operative medicine is one of the most spectacular topics of surgical research and will definitely change our approach. However, there are significant limitations, reducing the benefits of the robot (i.e., the lack of tactile feedback). On the other hand, based on the daily routine, laparoscopic surgical technique is tremendously evolving at the centers of expertise. Consequently, future systems have to offer technological advances beyond the standard laparoscopic technique. The further spread out of laparoscopy in almost all surgical subspecialties will guarantee a proper training of this technique. Mono-tasking robots (i.e., active camera arms) proved to be very effective in high-load laparoscopic centers in urology. Future directions should also focus on such devices, which can be used for the patients treated with the standard laparoscopic technique. This could be an instrument providing all six DOF or a mechanical manipulator. Further miniaturization of mechanics and motors will definitively enable such developments. Consequently, academic surgery should put special emphasis on future development of telerobotics, mainly because – in contrast with molecular biology or even nanotechnology – surgeons themselves will be actively involved in research, as well as in clinical application [43].

Summary

- Laparoscopy is handicapped by the reduction of the range of motion from six to only four DOF. Moreover, the standard laparoscopes allow only 2D vision. This has a major impact on technically difficult reconstructive procedures.
- During the last 5 years, there have been a lot of developments in the field of low- and high-cost robotics in urology.
- Early experiences with 6-DOF instruments (Radius) or even mechanical manipulators (MIM) are promising.

References

42. Schurr MO, Buess G, Schwarz K (2001) Robotics in endoscopic surgery: can mechanical manipulators provide a more simple solution for the problem of limited degrees of freedom? Minim Invasive Ther 10:289–293
Ultrasonic (US) imaging is very frequently used for diagnostic or interventional procedures. This widespread modality requires very good expertise of the operator, depending on the anatomical region to be explored and/or on the pathology type. Such an expert is not always available in close proximity to the patient. Because patient transportation to a suitable site may not be feasible or desirable, telemedicine may be very useful. However, in contrast to other imaging modalities, the transmission of series of US images to remote experts for later interpretation is not satisfactory. US image acquisition itself is really part of the expertise and conditions of the clinician’s ability to interpret the images. Indeed, the way the clinician moves the US probe on the patient body directly contributes to his/her understanding of series of images. This is why several groups worldwide explored over the last decade robotic tele-ultrasound; the objective is to develop robotic systems that move the US probe on the patient’s body and to give the control of those motions to the expert operator located in another site. In that way, the remote expert both acquires images and interprets them. Several prototype systems have been developed [1, 4, 6–8], but as far as we know very few clinical evaluations were done. Arbeille et al. [2, 3] report a global feasibility analysis of cardiac and abdominal US exploration for 20 patients and a clinical evaluation of remote examination of 29 pregnant women located in an isolated hospital of northern Morocco. Our objective is to contribute to the clinical demonstration of robotic tele-echography. In this chapter, we introduce the tele-echography robot (TER) system and describe technical and clinical experiments.
7.2 The TER System

7.2.1 System Architecture

TER is composed of two subsystems placed on two distant sites, the master site where the expert is located, and the slave site where the patient is. The master subsystem is composed of a haptic device connected to a computer workstation. This device, PHANTOM from SensAble Devices (Woburn, Mass.), is manipulated by the expert as a virtual US probe. In this way, he/she remotely controls the real probe, based on the US images he/she receives from the slave site, and with the help of a force feedback, is enabled fine control of the pressure exerted by the real probe on the patient’s body. The slave subsystem is composed of the US system and of a robot, both connected to a second computer workstation. The robot carries the real US probe and enables its movement on the patient’s body. Both subsystems include audio-video teleconferencing facilities. In this way, the expert can see the patient and can interact with him/her and with the staff person located at the slave site. This staff person (typically a nurse) helps with patient installation and system set-up. The two subsystems are connected by a telecommunication link, enabling transmission of the probe motion orders from the master site to the slave site; transmission of the US images, force information, and robot parameters from the slave site to the master site; and bidirectional transmission of audio and video data. This is summarized in Fig. 7.1.

![Fig. 7.1. General architecture of the TER system](image-url)
7.2.2 TER Releases

Two versions of the TER system were developed based on two slightly different robot architectures. TER-V1 [9] included a robot actuated by pneumatic muscles. Because control of the muscles turned out to be quite difficult and inaccurate, a second version of the robot was designed. TER-V2 [10, 11] is electrically actuated. A similar philosophy underlies both designs: having a light and safe robot that can be positioned directly on the patient’s body (typically on the

Fig. 7.2. TER-V2 robot. a The end-effector is translated by four straps (two DOF); it orients and applies fine translations (four DOF) to the US probe. b A real exam situation
abdomen) and the ability to automatically adapt to different patient sizes and to motions of the body surface, due to breathing, for instance. For this reason, both robots are composed of a first substructure with four flexible straps that allow translation movements of the second substructure on the abdominal surface; this corresponds to two degrees of freedom (DOF). The second substructure (four DOF) is dedicated to rotational movements of the US probe and to fine translational motions, ensuring a correct contact of the probe on the body. TER-V1 (respectively, V2) implements this substructure by a parallel (respectively, serial) architecture. TER-V2 robot can be seen in Figs. 7.1 and 7.2.

The PHANTOM desktop haptic device renders three-dimensional (3D) force information in a 160 × 120 × 120-mm workspace. Because the most important force component for probe control is the reaction force normal to the body surface, we alternatively developed a 1D force rendering system [5]. This haptic device has also the advantage of being a freehand system that gives the operator a much larger workspace than does the PHANTOM. This original haptic device has not yet been integrated to the TER prototypes.

7.2.3 Experimental Evaluations

Experimental work began by using TER-V1 for remote examinations of anatomical phantoms and then of a healthy volunteer. One radiologist and two gynecologists participated in this first stage. For the first in vivo experiment, the volunteer was located about 10 km away from the expert operator. Two Integrated Services Digital Network (ISDN) 128 kb/s connections were used.

With regard to TER-V2, the first testing was performed using a local area network (LAN) inside the Techniques for Imaging, Modeling, and Cognition (TIMC) Laboratory, Grenoble, France. Then ISDN connections were used firstly for quite local testing (10-km distance), then for longer distances. In October 2002, in the context of an exhibit, examinations were performed by physicians located in Toulouse, France, on an anatomic phantom placed in Grenoble (600-km distance). An ISDN 256 kb/s was dedicated to the experiment (128 kb/s for the US images – four images per second, 64 kb/s for the audio-video teleconferencing data and, 64 kb/s for the haptic and robot data). In December 2002, in the context of a French military telemedicine congress, a volunteer located in Grenoble was examined by physicians located in Toulon, France (300-km distance). An ISDN 512 kb/s enabled transmission of the US images (320 kb/s), audio-video data (128 kb/s), and haptic and robot data (64 kb/s). All those experiments were successful, and physicians were enthusiastic about TER potential capabilities for real clinical situations.
7.3 Clinical Experiments

The clinical experiments concern TER-V2, which we refer to as simply “TER” in the following.

7.3.1 Clinical Feasibility for Angiology Application

This first trial was intended to evaluate the ability to practice US examinations remotely in a real clinical context. Compared with previous experimental work, the telecommunication network was an experimental one: the 10 GB/s VTHD network connecting the Grenoble hospital to the Brest Hospital, Brest, France (1,125-km distance). The TER prototype was ready for evaluation in June 2003. Preliminary experiments showed that the architectural choices, controllability, and compatibility with the VTHD network were very satisfactory. In May and June 2003, four volunteers participated in preliminary testing. Based on the positive feedback from the radiologists and from the volunteers, the experimental work with patients began. It concerned patients suffering from aortic abdominal aneurysms (AAA) and/or from atherosclerosis. From July 2004 to March 2005, 58 patients were included by Grenoble and Brest hospitals. All patients signed the consent form after being informed about the aim of the research and content of the protocol, in conformity with the French bioethics laws.

Two complete systems were installed both in Brest and in Grenoble, enabling each site to be the master or the slave site. Both sites used the same US device for examination of the patients. Each included patient was examined both in the traditional way at his/her recruitment site – this initial exam was considered as being the reference one – and remotely using TER from the other site as concerns US control. Apart from the two involved physicians, another person (nurse, resident, or physician) was present during the TER exam at the slave site, in order to help install the patient, set up the robot, and use the US system (freezing the image, taking measurements, and tuning image-acquisition parameters). This person had to know how to use both the US device and the TER system, but he/she was not authorized to give any medical advice or comment during the exam.

Several pieces of information were recorded for both US exams (traditional/telerobotic) and compared:

- **Data concerning the pathology**: presence of AAA or stage of atherosclerosis and related measurements (for instance maximum anteroposterior diameter of the aneurism)
Data related to the exam: the two first scores were given by the operator and concerned the feasibility and the global quality of the exam. The third score was the evaluation of the acceptability by the patient. The duration of the exam was also recorded.

The study demonstrated that remote examination of patients was feasible. The four failures were due to technical problems (two dysfunctions of PHANTOM, one telecommunication link disruption, and one computer crash). Exploration of the anatomical structures was possible, and diagnostic elements were in agreement with the reference examinations. Remote measurements were repeatable, and intraobserver variability was good in comparison to literature data. Remote exams were a little longer in average. Satisfaction rate of the physician was lower in average when performing the exam remotely, while at the same time examinations are comparable as testify the other variables. Close proximity to the patient is probably an important element for the physician’s feeling of efficiency. Patients’ satisfaction rate was very good, except for two of the four patients for whom a technical problem occurred. Globally, the abdominal examinations of angiology pathologies with the TER system appeared feasible, safe, and reliable.

7.3.2 Focused Assessment Sonography for Trauma versus TER in Emergency Trauma Diagnosis

The second clinical study takes place in the context of emergency trauma diagnosis. When echographic examination is required to detect the presence of an abdominal internal lesion, two techniques are feasible, one consists of having a complete US exam from a radiologist, the other one, called focused assessment sonography for trauma (FAST), is a specific examination performed by the emergency clinician. As FAST is less sensitive than full US examination from a radiologist is, false negatives may occur. Since a radiologist may not be available at any time in trauma centers, one alternative would be to allow a radiologist to perform the examination remotely using TER. Thus, the study aims at comparing examinations performed by a radiologist using TER to examinations done by an emergency clinician using FAST.

The experiment takes place in the Grenoble North and South hospitals. The slave site is located in the emergency department of the South Hospital, and the master site is installed in the radiology department of the North Hospital. The two sites, distance of about 12 km, are connected by the private Ethernet 100 MB/s link of the hospital’s network. In case of suspicion of a visceral trauma, the patient has to be transferred from the South hospital to the North one for complementary examinations and specific care.
Seventy patients recruited by the emergency unit will be included in this study, which began in May 2006, after authorization of the hospitals’ ethical committee. Each patient is examined both using TER and FAST in a random order. As for the angiology evaluation, different pieces of information are collected:

- Diagnostic elements: in order to determine the agreement of the two examinations
- Other data such as duration of the exam, satisfaction rate of the clinicians, acceptance rate of the patient, etc.

At the time of this writing, 11 patients have already participated in the study. For 10 of the 11 patients, no visceral trauma was detected either with FAST or with TER, and this was confirmed by the patient follow-up. For the 11th patient, the TER examination was not satisfactory, and the patient had to be transferred to the North Hospital for direct examination by the radiologist. TER exams were in average longer that FAST ones (26 min versus 9 min). Of the 11 patients, transfer of 10 patients to the North Hospital was avoided, resulting in direct cost reductions for those patients. Potential pain for trauma patients, due to the strap’s pressure on the abdomen, was not observed. Of course, all planned patients have to be included before making any conclusion about the benefits of using TER for trauma diagnosis.

7.4 Conclusion

In this chapter, we briefly described the TER system and experiments aimed at demonstrating the technical and clinical feasibilities of the approach. Obtained results are quite encouraging, but ongoing work has to be finished before making any definitive analysis. Two clinical applications have been or are evaluated, but those are obviously not the only two that are concerned by such an approach; the spectrum is potentially very large (patients at risk who cannot be transported, patients in very isolated places [including space and sea], elderly persons, etc.).

Industrial dissemination of such systems raises issues related to cost evaluation, economical model (which hospital pays what to whom?) and legal issues (in case of problems, who is responsible for what?), etc. Those are complex questions that have not yet been satisfactorily answered, and the fact that two countries may be involved with different regulations and laws could make it even more difficult.
Summary

This chapter

- Outlined the clinical use of robotic tele-echography
- Introduced the TER system
- Described technical and clinical evaluations performed with TER

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References

8.1 Introduction

In surgical operations, medical staffs require rapid and safe diagnosis, operation planning, and surgical treatment. This is accomplished by using various kinds of data, such as those found in the operating field itself, vital signs, patient records, and communication among the staff. In telesurgery, an operating room and remote sites are connected with a network (Fig. 8.1). All kinds of information require digitization, which is then transmitted through a network and shown to staff, with digital devices for information support of telesurgery.

In telesurgery, medical staff in a remote site can only use shown data that are digitized and transmitted. Presentation of required information is important for information support of telesurgery. Only half of presentation obstructs surgical operation, and poor and complex presentation could delay surgical operation and lead to medical mishaps. Presentation quality of transmitted information affects quality of telesurgery.

This chapter focuses on technical issues for quality control in the presentation of required information in information support of telesurgery. Presentation quality for a remote staff depends on a presentation system and transmitted data, and the quality of transmitted data is controlled by transmission control of digitized data (Fig. 8.2).

Fig. 8.1. Information support for telesurgery
A presentation system is an interface of information support for telesurgery. Presentation quality for a medical staff depends on the sense of the staff. Usability of a presentation system directly, most probably, affects presentation quality of transmitted information. This section discusses technical issues for a presentation system, and focuses mainly on visual presentation, because vision is the main of the human senses, frequently referred as “visual capture” [15].

8.2 Presentation System

In a surgical operation, various kinds of information are used. A presentation system requires presentation of multiple data. For presentation of multiple data, use of plural presentation devices is the simplest way. However, too many devices cause complexity of system construction and presentation layout. Two or three presentation areas are, most probably, for intuitive reference of multiple data.

Switching of presentation contents and multiplex presentation in a single view is also applied to multiple data presentation to reduce number of presentation devices. However, for the switching method, a user should know about all available data to select the appropriate view. Multiplex presentation reduces resolution of each presentation data for sharing view area.

Tsukasa et al. [14] proposes a system for intuitive presentation of multiple data. The system is named the Telemedicine Cockpit.

The aim of the Telemedicine Cockpit is information support of real-time telemedicine that includes telesurgery. The Telemedicine Cockpit has its origins in the Surgical Cockpit System [4, 5].

Hori et al. [5] pointed out that additional use of circumstantial view with detailed view of an operating field is effective for telemanipulation task. A vi-
A visual interface system of the Telemedicine Cockpit consists of main view and subview. Figure 8.3 shows a prototype of the presentation interface.

The main view is used for precise and detailed view of main information for ongoing surgical operation. The subview provides a catalog of all available data for information support. A user selects required data for main view by referring to a catalog in subview.

An intuitive interface is an important issue for selecting the main view. The core task of all medical staff is medical treatment for a patient. In telerobotic surgery, a surgeon in a remote site should concentrate on manipulation of a surgical robot. An interface for selecting the main view requires not interrupting the surgical operation and communication among related sites. In the Telemedicine Cockpit, a “put-that-there” interface [1] is applied for an intuitive indication of a selected image on the subview. The put-that-there interface is a multimodal interface using gesture and voice command. To select the main view, a user points out a sample image of a target data and says “that” as a voice command for selecting the target (Fig. 8.4). The put-that-there interface is based on a metaphor of an intuitive daily act for target indication.

The Telemedicine Cockpit provides an intuitive interface for presentation control, that is, use of plural presentation devices and switching of presentation contents. Although presentation of required information is important for
telesurgery, presentation control is not the main operation of medical staff. An intuitive presentation interface is effective for faultless collaboration in telesurgery.

8.2.2 Presentation Methods for the Main View

In telesurgery, a method of precise and detailed presentation for the main view is also an important issue for effective and faultless information support. For a surgical operation, the medical staff requires precise location and posture of surgical instruments and human organs.

For precise and detailed presentation, high-definition vision is a basic method. A high-definition view provides immersive vision of target view. However, a single view cannot provide depth information of a scene view.

To provide depth sense with visual presentation, binocular stereovision is the simplest method. The stereovision includes a side-by-side display that uses a specially designed viewer, anaglyphs using glasses with an exact color match to the images, and liquid crystal display (LCD) shutter glasses [12]. Stereovision provides intuitive presentation of depth sense in a scenic view. However, precise presentation of location and posture is difficult in stereovision. Stereovision uses an optical illusion for providing depth sense to users.

Fig. 8.4. Selecting the main view from a catalog shown in subview
For precise presentation of location and posture of surgical instruments, Hori et al. [6] proposed three-side-view presentation. Three-side-view presentation provides a multiplexed view of working area from four different angles and a whole view of the area and three detailed views from three orthogonal angles (Fig. 8.5). The three-side-view method is a specialized method for precise presentation of spatial relationship in a target area.

### 8.3 Transmission Control

A presentation system is a system for presenting transmitted data. The quality of presentation is affected by the quality of transmitted data. Data transmission consists of three processes: sending, relaying, and receiving. The quality of data transmission is limited by time cost of each process.

Tanenbaum [13] points out that transmission quality is represented by four parameters: bandwidth, delay, jitter, and data loss.

Bandwidth is the average of transmissive data size per time unit. It corresponds to time to finish for transmitting data. Bandwidth means capacity of data flow.

Delay is an average of time cost from sending to receiving. Jitter is short-term change of delay time. Delay and jitter are affected by transmission distance, number of relay nodes, and processing performance of communication instruments.

Data loss is failure of transmitting data blocks. In Internet technology, data are transmitted as a sequence of small data blocks. Data blocks might be lost...
by electrical noise, overload of communication instruments, and other reasons. If error recovery technique, such as resending process in transmission control protocol (TCP) [10], is applied, then lost blocks are transmitted again. Delay and jitter are enlarged. If error recovery is not applied, then data transmission is failed by the packet loss.

Transmission quality affects data receiving and data presentation processes. To secure presentation quality, transmission control is applied. Transmission quality has two meanings, network-level quality and application-level quality. Network-level quality means performance limits for data transmission quality of a network. Application-level quality means requirements for data transmission quality of a telecommunication tool. Transmission control techniques are proposed for both network and application levels.

8.3.1 Network-Level Transmission Control

For securing transmission quality, a telecommunication line needs wide bandwidth, small delay, small jitter, and low data loss for providing enough telecommunication quality of required telecommunication tools. Network-level transmission control is traffic control of data flow for keeping quality of a telecommunication line. In the field of information and communication technology, the quality-of-service (QoS) control technique has been put to practical use for improving quality of data transmission [2, 3, 11]. A technical standard of QoS control is established in IEEE802.1d-2004 [7].

The basic concept of network-level QoS control is to guarantee required quality of network service. By using network-level QoS control, required transmission quality can be secured if the transmission quality of a telecommunication line is higher than the required transmission quality of a telecommunication tool. Network-level QoS control includes bandwidth reservation, buffering, and prior transmission.

Bandwidth reservation is applied for guarantee of available bandwidth. A network is shared by multiple data flows. Bandwidth of a network is distributed to telecommunication tools that share the line. A role of bandwidth reservation is distribution management of available bandwidth. If bandwidth reservation is not used and bandwidth of a telecommunication line is not enough, telecommunication tools scramble for limited bandwidth. Data transmission of each tool would be unstable. In the worst case, all communications of remote sites are stopped. When sending data size exceeds reserved bandwidth, exceeded data packets are abandoned.

Buffering works as a buffer for sending and receiving data of a telecommunication tool. A buffer of a sender stores sending data temporarily before sending to smooth data flow. A buffer of a receiver stores received data temporar-
ily before processing to smooth processing of received data. Buffering of data transmission is called traffic shaping because of the reshaping data flow. Buffering affects delay and jitter. If the buffer size is large, then delay is enlarged, although data transmission is smooth and stable. If the buffer size is small, data flow could be unstable by overflow from a buffer, although expansion of delay time is suppressed.

Prior transmission provides different quality levels of network services. Real-time telecommunication services, such as video streaming, audio streaming, and telerobotic operation, require high priority for data transmission. For non–real-time services, such as Web browsing, still-image transmission, and database access, low priority is good enough.

Network-level QoS control technique is required for securing stability of data transmission. However, setting up of network-level QoS control is difficult for medical staff. To use network-level QoS control, all relay nodes require being well controlled for reserving network resources. Technical support of network service providers is indispensable.

8.3.2 Application-Level Transmission Control

Network-level QoS control is a technique for guarantee of data transmission quality. The technique does not guarantee presentation quality. When network-level QoS is insufficient for required telecommunication tools, transmitting data could be destroyed in a QoS control mechanism. For securing presentation quality, a telecommunication tool requires intelligent control of application-level quality.

Additionally, information support for telesurgery is multiple data transmission of various telecommunication tools. Required telecommunication tools change dynamically during an ongoing surgery. Relative importance of the tools is also changed. Total management of transmission control is required. For total management of intelligent transmission control, Mori et al. [8, 9] proposed an application-level QoS control framework.

The QoS control framework in by Mori et al. [8, 9] is an integrated transmission control mechanism for multiple telecommunication tools, to save bandwidth and to keep robustness against data loss.

To reduce required bandwidth, transmitting data must be compressed or trimmed. For data compression, algorithms and parameters are different among telecommunication tools. A common interface and normalized parameters are required in total management of the data compression for multiple telecommunication tools. For data trimming, transmitting data must be trimmed to understandable data units for each telecommunication tool. In video streaming, for example, an image frame is a minimum data unit that is
understandable for a receiver (decoder). Well-controlled dispose of minimum data units is suitable for total management of transmitting data reduction. In the QoS control framework proposed by Hori et al. and Tanenbaum [6, 13], rejection control of minimum data units for each telecommunication tool is applied.

For rejection control of data units in application-level QoS control, rejection priority is applied to each data unit. Data units for rejecting are selected by evaluating the priority of each data unit and condition of a network. Rejection priority of each data unit is decided with importance of the data unit in a receiver application. When data transmission is obstructed by insufficiency of bandwidth or other reasons, the application-level QoS control rejects data units of low priority, for recovering smooth data transmission, and keeping continuous presentation of required information.

Priority control of data rejection is also used for reflecting relative importance among telecommunication tools. In information support for telesurgery, a network is shared by multiple telecommunication tools that transmit data of required information for surgical operation. Transmission quality of telecommunication tools must be balanced for securing quality of data transmission. In the application-level QoS control, rejection priority is defined to each telecommunication tool. The rejection priority of telecommunication tools is used for rejection control of data units. Rejection priority of each data unit is calculated from the rejection priority in a telecommunication tool and the rejection priority of the tool. Presentation qualities of telecommunication tools are totally controlled with keeping balance of relative importance among the tools.

Application-level control protects continuous presentation of required information against insufficient network-level quality. However, continuous presentation cannot be protected when network-level quality is lower than the required minimum quality for data transmission of required information. Both network-level and application-level controls of data transmission are required for securing presentation quality.

8.4 Data Generation

In data generation process, target information is digitized and processed to generate digital data for transmission. Quality of generated data is theoretical maximum quality of presentation.

Quality of generated data, most probably, includes spatial resolution, such as density and accuracy, and time resolution. Obviously, high-quality data improve presentation quality. However, spatial resolution is in a tradeoff relation
with time resolution. In video streaming, for example, the frame rate is in inverse proportion to available processing time for each image frame.

Practical quality of generated data depends on characteristic of a digitization target, digitization methodology, importance in ongoing surgical process, condition of data transmission, and necessity for a user. Data generation requires being individually adjusted according to the target and the situation.

### 8.5 Conclusion

This chapter explained the fundamental ideas of information support techniques for telesurgery. In telesurgery, information support has an important role. The medical staff in a remote site depends on transmitted data.

The most important aim of an information support system for telesurgery is to show data of required information to medical staff in remote sites, with enough quality for ongoing surgical operation. Presentation quality of transmitted data is the most important point for development of an information support system for telesurgery. Presentation quality of transmitted data affects quality of telesurgery. The ideas in this chapter are merely technical concepts for securing presentation quality. The meaning of “presentation quality” should be individually considered for every kind of information that is used in telesurgery.

System usability of an information support system is also important point for securing presentation quality, in addition to presentation quality of presentation devices. Complex manipulation mechanism interrupts judgment of the situation and ongoing surgical operation.

For future research, total management of telecommunication systems should be considered. In information support of telesurgery, various kinds of telecommunication tools must be managed and data transmission of each tool should be well controlled. High information support for telesurgery complexes system construction and system management for telecommunication. “Plug & Play” telesurgery, such as that proposed by Tsukasa et al. [14], provides one solution for integrated information support in telesurgery.

### Summary

- The most important aim of telesurgery information support is to show data of all required information to medical staff in remote sites, with enough quality for ongoing surgical operation.
Presentation quality depends on a presentation system and transmitted data.

A presentation system requires a well-designed presentation interface for intuitive presentation of multiple data and an intuitive manipulation interface for controlling the system without interruption of ongoing surgical operation.

Securing of presentation quality should be considered in each process of telecommunication, data generation, data transmission, and data presentation.

Transmission control is required both for network and for telecommunication tools.

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9.1 Introduction

In the current practice of minimally invasive surgery (MIS) and therapy, a surgeon is faced with problems such as a lack of dexterity because of restricted port access to the surgical site, a lack of fine manipulation capability because of the long surgical instruments, visual problems including motion sickness and loss of localization, and significant degradation of touch sensation (haptic feedback) for the surgeon from the instrument and its contact with tissue. Some of the reasons for such degradation in the feedback of touch are that (1) the instruments include hinge mechanisms with significant friction, (2) the cannulae through which instruments are inserted introduce friction [6], and (3) the contact forces at the instrument tip can sometimes be very small compared with the relatively large forces supplied by the arm to move the instrument mass and the unsupported hand. As a result of this degradation in the haptic sensation for the surgeon, surgical tasks requiring accurate feeling of tissue characteristics such as palpation are difficult to perform in the minimally invasive mode.

The recent use of robots in surgical interventions has solved several of the above-mentioned problems associated with non-robotic surgery. For instance, the end tool of the da Vinci Surgical (robotic) System (Intuitive Surgical, Sunnyvale, Calif.) includes a wrist that adds three rotations to the motions conventionally available in a minimally invasive environment, in order to improve the surgeon’s dexterity. However, the current surgical robotic systems have not yet been successful in terms of restoring feedback of instrument/tissue contacts to the surgeon. While the da Vinci system is capable of providing force feedback to the surgeon in some directions, this feedback is of low quality and disabled by the manufacturer, mainly because in the absence of force sensors on the surgical tool the interactions between the robot and the patient’s body are estimated from outside the patient and are consequently plagued by disturbances, bias, and noise caused by the entry port.
The absence of haptic feedback to the surgeon about instrument/tissue interactions is a safety concern in MIS. For instance, in a study involving minimally invasive cholecystectomy, it was observed that inappropriate and excessive application of force was a main cause of perforation of the gallbladder [2]. Such a safety concern is especially significant if visual feedback to the surgeon is degraded, e.g., if fluids from the patient’s body cloud the camera lens or the instruments leave the limited field of view of the endoscopic camera. On the other hand, the presence of haptic feedback can provide the surgeon with the required perceptual information for optimal application of forces, thus reducing trauma to tissue. It can also shorten the task completion times by eliminating the need for prolonging the maneuvers and awaiting visual cues as to the strength of the grip, the softness of the tissue, etc. Lastly, for instruments with restricted maneuverability as in MIS, haptic feedback is expected to improve the precision of manipulation. Research has been done to evaluate the influence of haptic perception on human sensory and motor capabilities for several surgical tasks. For instance, the ability to sense the puncturing of different tissue layers during the needle insertion task improves when users receive haptic feedback [1]. Moreover, study of the effect of force feedback on performing blunt dissection has shown that it reduces the number of errors, the task completion time, and the magnitude of contact forces [14].

9.2 Mechanisms for Haptic Teleoperation

A master-slave system for robot-assisted MIS consists of three main parts: a robotic arm that holds and controls the endoscope, robotic arms that hold and actuate the surgical instruments, and a human-machine interface (HMI) for the surgical robot. In such a system, the surgeon operates using the HMI (the master), while the surgical robot (the slave) follows the surgeon’s hand maneuvers transmitted from the HMI inside the patient’s body. For feedback of instrument/tissue interactions to the surgeon’s hand during master–slave teleoperation, it is imperative to have an HMI that can reflect forces to the surgeon’s hand, in addition to a properly sensorized surgical tool that can measure its interaction with tissue. The master and slave subsystems of a haptic teleoperation system appropriate for use in a minimally invasive surgery/therapy environment are described next.
9.2.1 Haptic HMI (Master)

The possible motions for an endoscopic instrument excluding the tip’s motions are limited to four: up and down rotation (pitch), side to side rotation (yaw), axial rotation (roll), and axial translation (insertion). In the haptic HMI shown in Fig. 9.1a, a PHANTOM 1.5A force feedback device (SensAble Technologies, Woburn, Mass.) is incorporated. A rigid shaft resembling an endoscopic instrument is passed through a fulcrum and attached to the PHANTOM’s endpoint, causing the motions of the handles grasped by the surgeon to be similar to those in endoscopic manipulation and providing haptic feedback to the user in these directions. The haptic surgeon-robot interface includes two additional mechanisms placed on opposite sides of the fulcrum for maximum static balancing, which provide haptic feedback in the gripping and roll directions (see the close-up views 1 and 2 shown in Fig. 9.1a).

The maximum force that the haptic interface is able to apply against the user’s hand in each of the three Cartesian directions is determined to be 14 N. In the gripping and roll directions, the maximum forces are 17 and 12 N, respectively. This means that the haptic interface can reflect large forces in all the five degrees of freedom if necessary, e.g., to provide the sensation of making contact with bone. In the haptic interface, the friction and gravity effects are determined and compensated for, such that the user does not feel any weight on his/her hand when the slave is not in contact with an object. This is important because, in MIS, the weight of an instrument hampers the accurate feeling of tissue properties by the surgeon. The workspace of the instrument covers a pitch angle of ±30°, a yaw angle of ±40°, a roll angle of ±180°, and an insertion depth of ±11 cm. Also, the finger loop’s gripping angle ranges from 0 to 30° (handle open and shut). This workspace encompasses the 60° cone known to be typically reached by endoscopic instruments during generic surgical tasks [4]. For a detailed description of this haptic HMI, see Ref. [11].

9.2.2 Sensorized Robot (Slave)

As discussed before, the surgical instrument (called the end-effector) needs to be capable of measuring instrument/tissue interactions. Due to the constraint on incision size in endoscopic surgery, the diameter of the robotic end-effector should be less than 10 mm. This space limitation means, among other things, that the pivotal motions of the tip jaws (e.g., grasper jaws) need to be actuated by a linear motion, preferably placed outside the patient. Moreover, no sensor should be mounted directly on the tip jaws due to sterilizability reasons. An end-effector that complies with the above requirements is developed and
attached to another PHANTOM device acting as the slave robot (Fig. 9.1b). Strain gauges are used to non-invasively measure the end-effector’s interactions with tissue in all the five degrees of freedom. The end-effector has a multistage assembly for tip open/close actuation through a linear mechanism (see magni-

![Diagram of Haptic HMI (master) and sensorized robot (slave)](image_url)

Fig. 9.1. a Haptic HMI (master), and b sensorized robot (slave) suitable for a minimally invasive environment
fied view 3 in Fig. 9.1b) and rotation about the main axis. A free wrist (made by links \(L_1, L_2, \) and \(L_3\)) is responsible for allowing the spherical motions of the end-effector centered at the entry point through the skin. For more information regarding this sensorized end-effector, see Ref. [8].

### 9.3 Communication and Control for Haptic Teleoperation

In a haptics-enabled telesurgical system, the flow of surgeon’s hand motion and instrument/tissue contact data from the surgeon side to the patient side and vice versa require bilateral communication between the master and the slave. For this purpose, the Virtual Reality Peripheral Network (VRPN) was used to establish network-based communication such that the slave can be haptically telemanipulated from the master.

Consider the master-slave system block diagram of Fig. 9.2, in which \(\theta_m, \theta_s, \tau_h, \tau_e, \tau_m, \tau_s, M_m, \) and \(M_s\) are the master and the slave positions, the force (or torque) applied by the user’s hand on the master, the force (or torque) applied by the slave on the remote object, the control commands (force or torque) sent to the master and the slave, and the master and the slave inertias, respectively. The goal of haptic teleoperation is to generate appropriate control commands \(\tau_m\) and \(\tau_s\) such that, regardless of the user and the object characteristics and behavior, there is correspondence between the master and the slave positions (\(\theta_m = \theta_s\)) and contact forces (\(\tau_h = \tau_e\)). This will ensure that the user has accurate perception of the object’s compliance. The four-channel control architecture shown in Fig. 9.2 ensures the satisfaction of the above-mentioned transparent teleoperation requirements (provided the gains \(a_1\) to \(a_4\) are chosen such that \(a_1 - a_3 = 1\) and \(a_2 - a_4 = 1\)). In our master–slave system, while the slave forces \(\tau_e\) can be measured directly thanks to the sensorized end-effector, we utilize the master’s dynamical model to

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**Fig. 9.2.** Block diagram of four-channel haptic master–slave control
estimate the hand/master contact forces $\tau_h$ as there is no force/torque sensor at the master. More details about this control method can be found in Ref. [12].

### 9.4 Experiments: Haptic Telerobotic Palpation of Soft Tissue

To assess the accuracy of transmission of task-related information to the surgeon’s hand, we consider a palpation task. Palpation is frequently used by surgeons to estimate tissue characteristics and greatly depends on haptic sensation. In our palpation tests, a user moves the master such that the slave considerably indents a soft object made of foam material and then moves the master back and forth for 20 s, while the slave is still in contact with the object. With the four-channel bilateral controller described above, the slave closely follows the hand position and also exerts a force (torque) on the object that matches the force (torque) applied by the hand on the master (Fig. 9.3). This means that the teleoperation system is acting transparently in terms of transmitting to the user the force (torque) versus deformation characteristics of soft tissue and its mechanical impedance, which are critical to the tissue palpation task. Additional experiments with different soft objects showed that haptic feedback can successfully provide the user with the ability to distinguish between tissues with different stiffness when probing them robotically.

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**Fig. 9.3.** Master–slave position and torque, after the slave is in contact with a soft object
9.5
Related Research Problems

9.5.1
Sensory Substitution for Haptic Feedback

It has been established that, due to major difficulties in design and technology, incorporating full haptic interaction in a complex surgical system such as the da Vinci demands fundamental system redesigns and upgrades, as well as long-term financial and research and development commitments from the manufacturer. However, in the short term and for some applications involving robotic surgery, it may be cost effective and advantageous to provide alternative modes of sensory feedback to the surgeon, e.g., as visual representation of haptic information. While force feedback remains a more intuitive means of relaying haptic information to the user, sensory substitution for haptic feedback may be able to provide sufficient feedback of an instrument’s contact with tissue and improve surgical outcomes at a lower cost than haptic feedback itself.

Haptic feedback can be substituted in more than one way, for instance by providing the surgeon with auditory, graphical, or vibro-tactile cues about instrument/tissue contacts. For instance, graphical display of haptic information as overlaid on or beside the endoscope view can relay haptic information to the surgeon, simply based on the size and/or color of the visual stimuli and without the need for force reflection capability in the HMI (Fig. 9.4).

![Fig. 9.4. Block diagram of master–slave teleoperation with several flows of sensory cues from the slave to the master](image-url)
In the context of surgery, for manual operation and robotic teleoperation of a surgical knot-tying task, the forces applied in the robotic mode were closer to the forces applied in the manual mode when the users were provided with auditory/graphical sensory substitution of haptic information [3]. In order to see the difference between sensory substitution and haptic feedback in the robotic mode itself, as shown in Fig. 9.5a, we used the master-slave system described earlier to compare the effect of haptic feedback with the effect of graphical feedback of haptic information for a lump localization task [10]. It was observed that the two feedback modalities resulted in comparable accuracies in finding the lump—an advantage of graphical feedback due to the lower system complexity required—while the task completion times were shorter with haptic feedback. The longer task time under graphical feedback was due to the fact that subjects had to constantly refer to the graphical display, in order to detect a significant variation in the contact force profile, which corresponded to a lump.

Utilizing the master-slave test bed, as shown in Fig. 9.5b, we also compared user performance for a telemanipulated soft-tissue stiffness discrimination task under visual (i.e., camera vision), haptic, and graphical modes [9]. Our goal was to study how effectively the graphical or haptic cues can replace a corrupted visual feedback. The motivation for studying this task is given by the fact that tissue palpation is one of the ways to detect cancerous tissue, which has a different stiffness compared to healthy tissue. It was found that graphical cueing leads to the highest rate of success in discriminating between two tissue

Fig. 9.5. Master–slave setup for performing a telemanipulated lump localization and b telemanipulated tissue stiffness discrimination
samples with different stiffness, while visual cueing incurs the highest risk of tissue damage (proportional to the energy delivered to tissue), which is because a subject would have to supply a significant amount of energy before tissue deformations are quantifiable.

9.5.2 Time-Delay Compensation in Haptic Teleoperation

An interesting control engineering problem is posed as a result of the presence of a non-negligible time delay in the communication media between the master and the slave. In the absence of haptic feedback to the surgeon, communication delays up to 600 ms have been found tolerable yet prolonging the completion times of surgical tasks [7]. In the presence of haptic feedback, however, such a delay can cause serious problems beyond merely slowing down the surgeon’s maneuvers. In mild cases, the delay corrupts the feeling of the remote environments as perceived by the user. In severe cases, it may make a teleoperation system unstable. We have used an approach based on passivity and wave theory to make the four-channel teleoperation architecture described earlier insensitive to time delays, by passifying the delayed communication channel [13]. As a result, stable teleoperation systems can be implemented with least interference on the user’s perception of tissue characteristics.

9.5.3 Haptics-Assisted Training

In MIS, the limitations on the degrees of freedom and the surgeon’s dexterity, the loss of tactile sensation, and the significant degradation in force sensation result in new perceptual-motor relationships, which are unfamiliar and challenging to learn. A possible solution to this learning challenge is to physically guide a trainee through the desired maneuver by force feedback from a haptic interface, thus helping the trainee to gain an objective understanding of the task required. Such haptics-assisted training can be done using shared control of two master HMIs and one slave robot [5]. One haptic device is held by the mentor, and the other is held by the trainee. The two haptic interfaces provide feedback forces to both the mentor and the trainee, proportional to the difference of their positions and inversely proportional to the control authority shared between them. At the beginning of the training, the slave robot is completely controlled by the mentor, and the trainee will receive large force feedback urging him/her to follow the mentor’s motions. As the training progresses, the trainee takes over the control of the slave robot and receives less force feedback. Toward the end of training, the slave robot is completely controlled by the trainee, allowing the mentor to assess the skill level of the trainee.
by feeling the reflected forces. The same mode of training can be used for tele-surgery, where the trainee will also gain hands-on experience on how to cope with delays in commands and audio/video signals.

### 9.6 Conclusion

A major deficiency of the current robot-assisted surgical systems is the lack of haptic feedback to the surgeon about instrument/tissue contacts. This chapter discussed the need for incorporating haptic interaction in robot-assisted interventions. To this end, a haptics-enabled surgeon–robot interface and a sensorized slave robot were described, which together form a master–slave teleoperator suitable for a minimally invasive environment. Using a four-channel haptic teleoperation control scheme and considering a soft-tissue palpation task, the transparency of the master-slave system in terms of accurate transmission of critical task-related information to the surgeon was experimentally validated. On the other hand, given that camera vision constitutes the only flow of data from the patient side to the surgeon side in the current surgical systems, it was discussed how alternative modalities for feedback of instrument/tissue interaction can improve task efficiency, while requiring a lower system complexity than haptic feedback.

### Summary

**Introduction**
- A surgeon is faced with several problems in minimally invasive surgery (MIS) including degraded haptic feedback.
- Robots have solved several of the above-mentioned problems. Yet, haptic interaction is not restored in the currently available surgical robotic systems.
- Haptic interaction is very important in master–slave surgery.

**Mechanisms for Haptic Teleoperation**
- A haptics-capable master interface and a sensorized slave robot are required.
  - Haptic master description.
  - Sensorized slave description.

**Communication and Control**
- The Virtual Reality Peripheral Network is used for master–slave communication.
The four-channel method is used for haptic teleoperation control.

**Experiments: Haptic Telerobotic Palpation of Soft Tissue**

- Using the master–slave system and the communication/control scheme described earlier, soft-tissue palpation tests are done.
- Plots of the master and the slave positions and forces, demonstrate the high fidelity of teleoperation.

**Related Research Problems**

- Sensory substitution for haptic feedback:
  - When a haptics-capable master interface is not available, it may be useful to provide alternative modes of sensory feedback about tool/tissue interaction to the user.
- Time-delay compensation in haptic teleoperation:
  - Communication time delay in teleoperation can corrupt the feeling of the remote environment as perceived by the user, and requires compensation
- Haptics-assisted training:
  - Haptics can be used to guide a trainee through the desired maneuver, thus helping the trainee to gain a kinesthetic understanding of the task required.

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10.1 Introduction

Innovations in ophthalmology have expanded greatly in recent years. Miniaturization of operating instruments, refinements in surgical technique, and use of laser delivery systems have all been recognized as key contributions to the realm of ocular surgery. Increased precision, decreased operating time, and improved surgical outcomes have directly resulted from these advances. We feel that the next major advancement in ophthalmology is the integration of robotic surgery.

Robotic systems have been utilized in the surgical environment for over 15 years. In 1992, a robot was first used to assist in a hip replacement surgery [1]. Since then, robotic surgical systems have proliferated [2]. In select disciplines such as urologic surgery [3–6], gynecologic surgery [7, 8], and cardiovascular surgery [9–11] robotic integration has become a mainstream development.

Multiple robotic surgical systems have been developed over the years, and the current standard is the da Vinci Surgical System [12]. This system incorporates a three-dimensional stereoscopic monitor with three robotic slave arms that are controlled by the surgeon. The surgeon is seated comfortably in the control console, where there is access to the monitor and hand controls to the robotic slave arms. The robotic arms have seven degrees of movement freedom that allow for the operator’s arm and wrist motions to be precisely mimicked. The robotic arms can be equipped with a variety of instrumentation to allow for specialized surgical procedures.

Robotic surgery addresses some of the limitations of traditional surgery, allowing for the completion of more advanced procedures. Advantages of robotic surgery include increased precision, improved range of motion, elimination of tremor, ability to maneuver in small anatomical spaces, and surgeon safety [13–16]. These are all central facets to advancement in any surgical field and by extension to ocular surgery.

The use of robotic ocular surgery in humans has not previously been performed. Robotics lends itself to ocular surgery in unique ways compared with
other surgical fields. For instance, lack of tactile feedback using the robot is not a drawback during ocular surgery, in contrast to other surgical disciplines. During cardiac and urological surgery, suture placement is partially gauged by tissue resistance to the suture needle. During ocular surgery, visual feedback is the primary system for gauging surgical maneuvers, and this is facilitated through the \textit{da Vinci}'s three-dimensional monitor. Elimination of tremor, while important in all surgical fields becomes imperative in ocular surgery [17, 18]. Within the small confines of the eyeball, every movement needs be precise and tremor free. Currently, the \textit{da Vinci} robot employs a tremor filtration component to allow this reality to exist.

There are several hurdles that need to be addressed before robotic ocular surgery becomes acceptable for human subjects. Refinements in surgical instrumentation need to be attended to, specifically the ability of the robot arms to grasp the instruments. Finer engineering and intuitive thinking should provide a solution to this issue in the near future. Viewing the posterior structures of the eye through the three-dimensional monitor is in need of fine-tuning. While both the anterior structures of the eye (cornea and lens) and posterior structures of the eye (retina and vitreous) are accessible to instrumentation
controlled by the robotic arms, the posterior structures of the eye require special lenses to provide proper visualization. These lenses are already in place on standard operating microscopes, and engineering a lens viewing system to fit one of the robotic arms is the likely solution in the future.

Ocular surgery is a unique field that likely will benefit with maturation of robotic technology. Minimally invasive instrumentation, precise movements, tremor reduction, and improved maneuverability all are key advancements that robotic integration can provide.

10.2 Institute and Global Experience

Recently, the feasibility and applicability of robotic ocular surgery was analyzed through a series of pioneering studies [19, 20]. First-time demonstrations of external ocular surgery, anterior segment surgery, and posterior segment surgery while utilizing the da Vinci surgical robot have been performed at the Center for Advanced Surgical and Interventional Technology at the University of California, Los Angeles (UCLA).

The da Vinci Surgical System consists of two primary components, a control console that allows the surgeon to manipulate the robotic arms remotely, and the robotic apparatus with three arms (or four arms in a recent addition) that holds a dual-channel endoscope (Fig. 10.1). An ocular viewfinder on the console provides a stereoscopic view of the operative field from the endoscope. The surgeon manipulates the controls using fingers, wrists, hands, and arms, while a computer processor filters, scales, and relays the movements to the robotic arms and instruments. There is no measurable delay between the movement of the surgeon’s controls and the mirrored movement of the robot apparatus. The processor eliminates tremors and minor movements. The architecture of the instruments and the da Vinci system allows the surgeon to insert, extract, roll, pitch, yaw, and grip with the robotic tools. The robotic arms are capable of tilt in two planes, achieved with two “elbow” joints.

10.2.1 External Ocular Surgery

Robotic external ocular surgery was performed on harvested porcine eyes that were given a laceration along the length of the cornea. The primary objective of the study was to demonstrate that closure of an external ocular wound was possible using the da Vinci Surgical System.

The corneal lacerations were each made 8 mm in length and 90% depth, resembling a true-to-life corneal laceration sustained during ocular trauma.
The lacerated eye was placed in a Styrofoam mannequin head in the anatomic position. Visualization of the eye was achieved with the three-dimensional endoscope placed above the globe in the midline, thus mimicking the axis of standard ocular surgery using an operating microscope. The robotic arms were placed on either side of the globe at approximately 45° angles, resembling the same approach used by an operating surgeon to maximize exposure to the ocular surface.

Three separate surgeons performed the procedure while positioned at the system console located across the operating room suite from the robotic apparatus. The robotic arms were each equipped with sterile Black Diamond micro forceps (Fig. 10.3). Each surgeon placed three 10-0 nylon filament sutures using the robotic arms to hold and manipulate the suture needles. The operating time for wound closure for each surgeon was recorded using a digital timer, and the procedure was documented in full with still and video photography. A human assistant located next to the robotic apparatus cut the sutures when necessary (Figs. 10.4, 10.5, 10.6).

Several observations were noted at the conclusion of this study. First, the dual-channel endoscope provided excellent depth perception for the surgeons. Key surgical landmarks were clearly and readily identifiable. Second, it was also
noted that refined surgical instrumentation would improve the control of suture placement. Currently, the micro forceps are tailored toward placement of 7-0 sutures in cardiac surgery. Further miniaturization of the forceps would facilitate more delicate maneuvers and enhance grasping of smaller objects.

This study concluded that robotic ocular microsurgery was a technically feasible feat. It demonstrated the need for design driven engineering improvements and confirmed further testing in scope of ocular surgery were necessary.
Fig. 10.5. Robotic micro forceps grasping cornea and inserting first suture

Fig. 10.6. Robotic tightening of suture
10.2.2 Anterior Segment Surgery

Robotic anterior segment surgery was attempted on a porcine eye cataract model as a study of feasibility. First, a microkeratome blade held by the robotic forceps was used to create a clear corneal incision. Next, a viscoelastic gel was inserted by an assistant into the anterior chamber of the eye in order to stabilize the intraocular structures. A cystotome (angled needle tip modified as a surgical knife) held by the robotic forceps was then used to cut a circle in the anterior capsule of the lens. This critical step of cataract surgery proved to be a difficult task to emulate while using the robot.

Proper wound entry is essential when performing cataract surgery and any slight deviation from the normal can create tension on the eye surface leading to distortion of the intraocular contents. The da Vinci Surgical System was originally designed for laparoscopic surgery and subsequently was given a high stable point of rotation to avoid inadvertent tension on the skin opening during surgery. This configuration was counterproductive when performing anterior segment surgery, in which a low stable point of rotation is desired. While wrist movements of the surgeon are translated and mirrored by the robot, arm movements were not intuitive and prone to surgical error.

In summary, cataract surgery was not feasible at this point in time based on the limitations of instrumentation. The angle of approach needs to be lowered to allow for easier wound entry and surgical manipulation. While the current configuration of the robotic apparatus does not allow for this change, future engineering refinements should yield a solution.

10.2.3 Posterior Segment Surgery

Robotic posterior segment surgery was assessed via a 25-ga pars plana vitrectomy demonstration using a porcine eye model. In preparing the robotic system for posterior segment ocular surgery, commercially available intraocular instruments were adapted for use with the robotic forceps. Small metal plates were fixed to the handles of a 25-ga vitreous cutter and endo-illuminator to allow durable grasping with the robotic forceps (Fig. 10.7). The intraocular instruments were stationed next to the eye on a magnetic stand to facilitate instrument exchanges.

The initial step was to inflate a harvested porcine eye with a balanced salt solution to reach approximate ocular tonus. The prepared eye was then secured to a mannequin head in the anatomical position. The head was placed on a surgical table positioned directly under the robotic apparatus. Visualization of the eye was achieved with the system’s three-dimensional endoscope, placed above...
Fig. 10.7. Metal plates were fixed to the 25-ga instruments. The instruments were held with a magnetic stand to ease grasping and storage during surgery.

Fig. 10.8. In addition to axial motion, the wrist-like tips of the robotic instruments have roll, pitch, yaw, and grip to facilitate delicate manipulations.
the mannequin head, and centered on the globe. The arms of the robot were placed lateral to the axis of the endoscope on either side of the globe.

Ten three-port 25-ga pars plana vitrectomies were performed in this study. Using the robotic forceps, an infusion trocar was placed approximately 3 mm posterior to the limbus in the inferotemporal quadrant of the globe (Fig. 10.8). Next, an infusion cannula was placed in the trocar with the robotic forceps, and turned on by a human assistant. Two additional trocars were placed in a similar fashion 3 mm posterior to the limbus: one in the superotemporal quadrant and one in the superonasal quadrant. A disposable wide-angle vitrectomy contact lens was placed on the cornea by an assistant.

The vitreous cutter and endo-illuminator were grasped from the magnetic stand with the robotic forceps and placed through the superior trocars into the globe (Fig. 10.9). Under a high-magnification view, a core vitrectomy was performed. At the end of the vitrectomy, the instruments were removed from the eye and placed on the magnetic stand. Finally, the trocars were removed from the eye with the robotic forceps.

Several observations regarding robotic movements were noted at the conclusion of the study. Control of the intraocular surgical instruments was per-
formed with relative ease by moving the tip of the robotic forceps. The surgeon’s wrist movements translated to instrument manipulation almost intuitively with no notable difficulties despite lack of prior experience with the robot. For example, insertion of the instruments into the globe and minute adjustments during the vitrectomy went easily. Arm movements, however, were not as intuitive as wrist movements. Capable of two-plane tilt without joint rotation, the robotic arms do not mirror the exact movements of the human arms. Picking up an instrument from the magnetic stand and moving it toward the eye proved to be slightly difficult. In addition, the endoscope prevented positioning of the robotic arms in a vertical alignment. This limitation posed a problem during the vitrectomy, rendering the outer vitreous gel approachable only with contralateral instruments.

Visualization was a challenging aspect that will require refinement. Camera realignment was frequent and time-consuming. For instance, each time an ocular instrument was fetched from the magnetic stand, the endoscope had to be tilted and zoomed out to facilitate adequate view. Camera repositioning was also required for left-to-right exchanges of the instruments, as well as during removal of the instruments while performing the vitrectomy. Lack of an optical inversion system prevented the use of standard wide-angle vitrectomy lenses. Last, while the resolution of the endoscope’s camera was of high quality, it did not yield the detail of an optical microscope routinely used in intraocular surgery.

One potential solution for the visualization problem is to add a wide-angle camera that provides a complete view of the entire operating field. The image from this wide-angle camera can be overlaid in the corner of the surgeon’s main view. This would allow the surgeon to have a broad view of the entire surgical field that can be referred to during instrument exchanges.

10.2.4 Conclusions

The da Vinci Surgical System in its current design is acceptable for external ocular surgery, but it presents two major limitations for intraocular surgery. First, having a stable point of rotation above the robotic wrist rendered intraocular movements less controllable. Second, intraocular visibility using the robotic endoscope was inferior compared to the view obtained through an optical microscope.

The potential benefit of a robotic system for ocular surgery is unclear. Ocular surgery has already employed minimally invasive techniques for intraocular procedures, providing minimal trauma, rapid recovery, and excellent outcomes. With the majority of non-robotic procedures, surgeons have both good control and excellent view with an optical microscope. In addition, mane-
The opportunities for robotics in ocular surgery are those interventions for which only the robotic system renders possible, or noticeably simplifies the current approach. Reducing the time needed for surgery, for example, can be one possible merit of having such a system. Further refinements in engineering will likely open the door to improved control over that of a trained human hand and thereby make robotic surgery a safer alternative compared to traditional surgery. To this end, our laboratory is actively developing newer techniques and instrumentation. The foundation is now in place for continued investigation of the feasibility and applicability of robotic systems for ocular surgery.

10.3 Education and Training Opportunities

The Center for Advanced Surgical and Interventional Technology (CASIT) at UCLA is a large research facility that includes the Gonda Robotic Center, integrated operating room suite, and telecommunications center.

The mission of CASIT is to define the state-of-the-art surgical and interventional technology and to revolutionize surgical education and training. The goals are to enable the development of precision in the performance of minimally invasive procedures, to deliver novel surgical and interventional therapies, and to develop a greater interventional capacity through robotics and simulation.

CASIT collaborates with various organizations and entities, including the UCLA Department of Bioengineering, the California Nanosystems Institute, the Center for International Emergency Medicine, Jet Propulsion Laboratory, UCLA interventional services, and UCLA students and residents. The input from each of these groups is fed through CASIT, and new research, clinical, and training outcomes are tested at our beta test centers in the UCLA hospitals and CASIT’s laboratories.

While there are no formal training modules available yet for robotic eye surgery, we envision this to become a reality. A short-term goal is to have resident ophthalmology physicians rotate through the CASIT laboratory in order to gain exposure to robotic eye surgery and its potential applications.
10.4 Future Directions

10.4.1 Telerobotic Surgery

The feasibility of telesurgery was demonstrated in 2001 when the first transatlantic robotically assisted remote surgery was performed on an animal model [21]. This was followed by transatlantic robot-assisted laparoscopic cholecystectomy in a human being [22]. Since then, telesurgery has been demonstrated successfully on multiple occasions [23]. Ocular robotic telesurgery may also be feasible, bringing emergency eye care to distant and hard-to-reach locales, such as a battlefield. Ocular surgery would be particularly suitable to telesurgery as there is minimal chance of severe blood loss and hence a more controlled environment exists.

The major obstacle for performing any remote surgery is the lag time needed for information to travel between the robot and a distant operator [24, 25]. While performing ocular surgery, movements are usually slow and methodical, with emergent or quick action being an exception. Still, precise and timely movements should be the goal of any surgery. One possible solution is for the robot to perform pre-programmed tasks via real-time input [26]. This task automation would be effective in routine portions of surgeries such as insertion of trocars and infusion cannula. In a random situation such as repairing a corneal laceration, task automation would not fare as well. Likely, future improvements in bandwidth technology should alleviate the significant lag time that presently exists.

10.4.2 Telerobotic Mentoring

Telementoring is the creation of a virtual classroom, and current robotic and audio/visual infrastructure allows for this to exist. In the first demonstration of telementoring, a laparoscopic colectomy was performed by a novice surgeon taking instructions from an expert surgeon located across a medical campus [27]. Since then, telementoring has been implemented across continents with improving success [28–33].

Ocular surgery lends itself considerably well to a mentoring process, as one-on-one training has been the standard in the field. We envision a lead ocular surgeon with audio, visual, and physical connections to a remote operating room lending advice and providing physical assistance to the novice remote surgeon.
10.4.3 Novel Imaging Acquisition

Ultrasound imaging capabilities can be added to the robotic arms to allow for telerobotic data transmission. For instance, a robotic arm with a built-in ultrasound can assess a patient with a new vitreous hemorrhage. The ultrasound unit can either be manipulated from a remote site or controlled via task automation. The ultrasound scans would be transmitted in real time to the remote surgical team for review.

10.4.4 Conclusions

Robotic ocular surgery, telesurgery, and telementoring will make progress as engineering refinements, programming breakthroughs, and bandwidth expansion continue to take shape. Challenges for future robotic design exist through engineering of finer instrumentation, integration of novel imaging, and automation of routine tasks. Although still in its infancy, robotic ocular surgery is a cutting-edge development that will eventually have far-reaching scope and applicability.

Summary

- Robotic ocular surgery is in its infancy compared with advances made in other surgical disciplines.
- Opportunities for robotic ocular surgery include increased precision, elimination of tremor, decreased operating time, and increased surgeon safety.
- Improvements necessary for the advancement of robotic ocular surgery include miniaturization of instruments, task automation, robotic arm realignment, and viewing system re-design.
- Telerobotic surgery and telerobotic mentoring are both future endeavors with immense applicability for ocular surgery.

References

11.1 Introduction

11.1.1 The Importance of Simulation

As the length of medical training time decreases and the expected knowledge base of healthcare providers increases, simulation is often being called on as an educational supplement to real-world experiences [13, 15]. This is especially true in those cases where physical distance is a hindrance to receiving proper medical training [9, 16]. Regardless of whether or not distance is the issue, medical simulators have recently been shown to be efficacious, supplemental educational aids when it comes to teaching the complexities of surgery [7] and emergency room medicine [14].

At advanced, complex training levels, such as learning by way of the surgical simulator, it is important that the appropriate clinical clues be incorporated into simulated systems, in order to support high-level decision making [5]. Students often complain that the lack of clinical realism associated with many medical simulators is an important limitation [5]. In order to create a strong sense of presence in the virtual environment, the traditional modalities of touch, hearing, and vision must be superseded. For these reasons, in addition to the fact that simulators play a supplemental role to real-world clinical experiences, it is important that virtual technologies provide the student with as much realism as possible, including details that have historically been considered technically out of reach, such as appealing to the human sense of smell.

11.1.2 The Sense of Smell and Medicine

In traditional Chinese medicine, the sense of smell has always been recognized as a valuable medical diagnostic tool [3]. Doctors are taught to use the
sense of smell to recognize disorders even before a patient begins exhibiting symptoms, and the importance of smell, for the purposes of diagnosis, can be universally applied to the practice of medicine in general [1, 4, 19]. For example, clinicians are trained to recognize the smell of pears (acetone) on a patient’s breath as being indicative of diabetes [1, 4, 6, 19]. Syphilis, kidney failure, abscesses of the lung, uremia, scurvy, liver failure, typhoid, scrofula, smallpox, rheumatic fever, diphtheria, pneumonia, and scarlet fever are also just a few of the conditions described by clinicians as having distinctive odors. In addition, odors that can be associated with surgery, such as infected wounds, human tissues, and human body fluids such as blood or bile, have also been considered in terms of telepresent surgical applications [12].

### 11.2 Scent Technology

There are a number of companies currently developing computerized olfactory technologies. Some of the more widely known developers include Aromajet, British Telecom, Aerome, Trisenx, Osmooze, AC2i, ScentIT, ScentAir, and DaleAir [10, 11]. Although their designs vary, the fundamental supporting technology behind computerized scent generally falls into one of five categories: inkjet systems, wax-based systems, airbrush systems, microencapsulated systems, or heated-oil systems. When considering medical simulators that incorporate the sense of smell into their framework, the design of the olfactory system is less important than the fact that the technology exists. Because scents can be customized, depending on the simulated environment, any contemporary computerized scent device could be made to work.

One of the more common types of computerized scent technologies is the heated oil and fan design. The “Scent Dome,” an example of this type of design, can be purchased from a Georgia-based company called Trisenx [17]. The Scent Dome (Fig. 11.1), which is approximately 14 cm wide, 20.5 cm long, and 6.5 cm tall, plugs into a standard COMM or USB port and is powered by four D batteries or optional adapter. Each Scent Dome comes standard with one interchangeable scent cartridge [18]. Each scent cartridge contains 20 distinct chambers, with 20 distinct vials of preselected scented oils, the combinations of which can create thousands of aromas.

The Scent Dome itself is controlled by way of a graphical user interface. This proprietary computer software, called Senxware, allows the user to mix and match aromas by way of a virtual beaker or to activate one of the preprogrammed aromas [18]. After a scent is created, and the Scent Dome software activates the unit for dispersion, the software communicates with the Scent Dome via a serial (or USB) connection, at which time the selected chambers are
heated up and the aroma is blown out of the Scent Dome by way of a small fan. Scents can be programmed to run at specific intervals, for specific lengths to time, and triggered by customized software. The intensity of an aroma is controlled by the length of time a chamber is activated.
11.3 Education And Training

11.3.1 Practical Applications

At the time of this writing, there were no known medical simulators that incorporated computerized scent technologies into their framework. Nevertheless, there are areas where the technology could be practically applied. When it comes to actual telesurgery, much of the existing scent-related literature broaches the subject in terms of simulated environments that both detect and reproduce surgically related scent. For example, in Keller’s model [12], an electronic nose identifies odors in remote surgical environments and then electronically transmits the electronic signatures for those odors over a computer network to a separate location, where the odors are recreated for the coaching surgeon’s benefit.

A more practical application of scent technology would be from a medical educational perspective. The technology could be rather easily incorporated into medical simulators. To demonstrate how this would work, the technology is modeled below in terms of real-world emergency room patient and haptic surgical simulators.

11.3.2 Computerized Scent and Patient Simulators

It is a well-documented fact that the sense of smell plays an important role when it comes to patient diagnostics [1, 19], especially in the area of emergency room medicine [4]. Clinicians must learn to use all their senses in order to make quick diagnostic decisions, especially considering the fact that some patients are unable to communicate (because of either the incapacitation or the language barrier).

Historically, training emergency room staff to recognize the odors associated with specific poisons and diseases has been a manual process [4]. Gibbons [4] describes the process used at New York City’s Bellevue Hospital, whereby students are presented with a tray full of test tubes, each presumably representing one of the more commonly encountered medically related odors, which they are then expected to learn to recognize. Not only would computerized olfactory devices help to modernize this process, but the technology could also be incorporated into emergency room simulators to both increase the simulated realism and accelerate the learning process.

To use a real-world example, advancements in networking technology have created the ability to provide simulated medical training over great distances, a
fact recently demonstrated by the collaborative emergency room simulation effort between the Center for Excellence in Remote and Medically Underserved Areas (CERMUSA) at Saint Francis University (SFU), the Uniformed Services University of the Health Sciences (USUHS), and Internet 2 [14].

Using a high-speed Internet connection, an emergency room simulator was virtually connected between USUHS, in Bethesda, Maryland, and a group of SFU physician assistant students located in rural Loretto, Pennsylvania [9, 14]. In Loretto, information regarding the simulated emergency room patient was displayed on four different flat-screen monitors for the students. Two of the monitors relayed an overall view of the simulated emergency room at USUHS, while the other two monitors relayed information regarding the vital signs of the simulated patient (see Fig. 11.2). Based on the virtual information provided by these live video feeds, SFU students conferred their patient assessments to doctors at USUHS, who then performed the emergency procedures as recommended.

Consider the following simulated example. A patient comes into the emergency room complaining of stomach cramps, vomiting, and having bloody urine. During the initial assessment, it is found that the patient also has a fever and an irregular heartbeat. In addition, the patient’s breath exhibits a strong odor of garlic. Because of this odor, the veteran physician might immediately recognize these symptoms as indicative of arsenic poisoning, while the medical student might remain perplexed. In order to accomplish the simulation of emergency room-related odors, such as those indicative of diabetic shock, poisoning, liver failure, etc., some types of computerized olfactory devices would have to be incorporated into each location of the simulated environment (Fig. 11.2).

In this particular example, the odor of garlic would be created using computerized olfactory technologies at both physically simulated locations. On the emergency room simulation side (in this case at USUHS), the scent device would be directly incorporated into the simulated patient (Fig. 11.3). On the classroom side (at SFU), the scent device would be incorporated into the existing networked computer system.

When the odor of garlic is activated on the patient simulator, a signal would be sent over the IP network to the scent device located in the SFU classroom. At that point, the SFU scent device would begin simultaneously emitting the odor of garlic for the students. The students could then offer procedural recommendations, based not only on the vital information displayed by way of the live video feeds, but also on the olfactory information being emitted from the scent device.
As in the previous example of incorporating computerized smell into emergency room patient simulators, the same principle would apply to haptic surgical simulators. Consider the following example. Using a high-speed network provided by the Center for Networking Technologies for the Information Econ-
omy (CeNTIE), representatives from the Stanford University School of Medicine (California) and the Commonwealth Scientific & Industrial Research Organization (CSIRO) of Australia performed a virtual laparoscopic cholecystectomy (surgical removal of the gall bladder) using three-dimensional haptic simulators [7, 16].

During this simulation, which was being viewed in three dimensions by audiences at each location, two surgeons, one playing the role of resident in training at the Canberra Convention Center in Australia and the other playing the role of instructor at Stanford University in the United States, simultaneously performed the simulated procedure on a stereo image of a gall bladder and surrounding organs [7]. Each having control of one of two virtual surgical tools at one time [16], as depicted in Fig. 11.4, the haptic simulators allowed each surgeon to not only see and hear what the other surgeon was doing in real time, but also to feel tissue resistance and the virtual manipulations (spatial retractions and organ dissection) being made by the other surgeon [7, 9].

At the SimTeC T interactive simulation demonstration, the surgical instructor illustrated how the haptic simulator dealt with surgical mistakes and mishaps [8]. During a normal laparoscopic cholecystectomy, the gall bladder is retracted just enough to allow for the proper dissection of the organ. In order to demonstrate the haptic effects of over-retraction, the instructor used the surgical grasper to apply more force than was necessary, which ultimately resulted in the virtual rupturing of the gall bladder. This rupture in turn resulted in the simulated release of bile into the abdominal cavity. This event, in addition to any medically simulated surgical event, could be used to trigger the release of a virtual odor using a computerized olfactory device.
As with the emergency room simulator, in order to accomplish the simulation of surgically related odors, such as fetid blood, bile, infection or even the smell of smoke, some types of computerized olfactory devices would need to be incorporated into each haptic simulator (Fig. 11.4). Referring to Fig. 11.5, assume that the following situation has occurred during the simulation. The resident in train-
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ing, at haptic workbench A, and in control of tool 1 (a grasper), has used excessive force in the retraction of the gall bladder (or some other organ as modeled). At the very moment when the tissue was virtually ruptured, the smell print (or abbreviated code) for bile (odor 1) is sent to both haptic simulators, which in turn activates the computerized scent device. Haptic workbench A receives the smell print via a serial connection, while haptic workbench B receives the smell print via a high-speed network connection. At this point, the computerized olfactory device, which has been incorporated into both haptic simulators, begins reproducing the odor of bile at both locations. Because the devices can control the intensity of the odor, and not all surgical damage is immediately apparent, differing levels of damage can be virtually represented. If a botched surgical event is not severe enough to render any apparent, visual damage, then the faint odor of leaking body fluids might indicate to the surgeon that there is a problem.

11.4  Future Directions

Computerized scent technology, at least at the time this chapter was written, could easily be described as bleeding-edge technology. Incorporating existing scent technologies into any contemporary medical simulator would not be
technically difficult to accomplish. It is when we enter the human into the equation that we began experiencing difficulties. Smell is, in and of itself, a complicating factor, as people often interpret the same odor in different ways [2]. The science of smell is a complex issue, and little success has been achieved in creating adequate classification schemes [2, 11]. The quality of any medically reproduced odor must be high. Getting a panel of experienced medical professionals to agree that a specific odor reproduction was indicative of a specific medical condition could prove to be difficult. In addition to this, odor intensity and duration of presentation also play significant roles in the efficacy of scent delivery [2]. For example, saturation becomes an issue if too many scent cues, with long intervals, are presented to the user in the same session.

In addition to the odor-incorporative simulators modeled here, computerized olfactory technologies have applicability to the field of medical education in general. One potential application of the technology would be to incorporate it into all types of medically related simulators, whether they are static or networked, surgical or nonsurgical. Depending on the application, exposing students to the various medically related odors, associated with all types of disorders, would be a major educational benefit.

Summary

- Simulation is an educational supplement to real world experiences.
- Sense of smell in medicine is a valuable medical diagnostic tool.
- A number of companies are currently developing computerized olfactory technologies.
- Scent technology can be incorporated directly into the haptic surgical simulator.
- Incorporating existing scent technologies into any contemporary medical simulator would not be technically difficult to accomplish. In addition, computerized olfactory technologies have applicability to the field of medical education in general.

References

12.1 Background

Telemedicine is defined as the use of telecommunications and information to support delivery of healthcare, where distance separates the provider and the patient [14]. Telementoring is an educational technique in a slightly different dimension-mentoring through the use of telecommunications. With the onset of the Internet, access to the “more experienced” has been on a rapid increase, and with the increasing applications of telecommunication network in medicine, this access has now reached a state wherein the remotely placed surgeons can get the help of centrally placed experienced surgeons in performing complicated surgeries/procedures that may require expert advice during surgery for intraoperative decision making. Besides intraoperative assistance, as has been highlighted by several authors earlier, the authors feel that an additional dimension to telementoring involves incorporating all the events, wherever a mentor’s input is needed for the overall clinical care of the patient, such as aid in diagnosis, preoperative treatment planning, and postoperative care. The application of telementoring in surgery has been utilized in various subspecialties like urology [5, 13], gastrointestinal surgery [16, 17], neurosurgery [6], vascular surgery [2], and now in endocrine surgery [1, 10, 19].

Endocrine surgery, though well established, is a relatively new subspecialty of general surgery, with a few dedicated centers and surgeon worldwide. The limiting factor for growth of this subspecialty in developing countries, apart from availability of few dedicated training centers, includes many local logistics problems. In order to create a critical mass of trained endocrine surgeons, keeping in mind the country situation, one of the options is to render short-term training to experienced general surgeons in medical colleges and large community hospitals having special interest in endocrine surgery. Telementoring is an effective tool for continued reinforcement of endocrine surgical training and helping community surgeons in overall patient care. Initial experience using this telemedicine module, in Department of Endocrine Surgery at the Sanjay Gandhi Postgraduate Institute of Medical Sciences (SGPGIMS), Luc-
know, India, has yielded encouraging results [9]. The minimum requirements for setting up telementoring facility include (Fig. 12.1) the following:

- **Receiving end:**
  - Digital video camera set up in the operating room (stand mount/in light)
  - Camera control unit for laparoscopic image capture
  - Codec facility for compression and onward transmission of images
  - Two-way audio–video conference facility
  - Room video camera set-up
  - Large-size display device (television/LDC TV/plasma panel)
  - Video network between OR and telemedicine hub
  - Broad band communication media of 512 Kbps and above (ISDN/IP)

- **Mentor end:**
  - Two-way audio–video conference facility
  - Broad band communication media of 512 Kbps and above (ISDN/IP)
  - Display device
12.2 Global Experience

Very few centers in the field of endocrine surgery have published their experience in using telementoring for surgical skill enhancement and knowledge sharing. Ushiyama et al. in 2003 [19] reported successful telementoring and removal of an aldosteronoma (adrenal tumor producing hypertension, 2-cm left adrenal tumor) in a 52-year-old male with primary hyperaldosteronism. An experienced laparoscopic surgeon supervised a less experienced surgeon from a control room about 100 m away. Mentoring was accomplished over a fiber optic cable employing real-time video imaging, two-way audio-video communication. The procedure was successfully performed in 195 min, with minimal blood loss. The patient recovered without complications and returned home on seventh postoperative day. Rafiq et al. [11] reported their experience in assessing the feasibility of mentoring and consultation to a remote audience with visual transmission of the surgical field, which is otherwise very difficult to share. Twenty-five thyroidectomy explorations in 15 patients were monitored and transmitted bi-directionally with audio and video data in real time. Remotely located surgical trainees (n = 4) and medical students (n = 3) confirmed seven different anatomic landmarks during each surgical procedure. Bruschi et al. [1] reported their preliminary experience with laparoscopic telementored adrenalectomy. During a 10-month period, eight laparoscopic telementored adrenalectomies were performed at two different sites, 430 km apart. Six unilateral laparoscopic adrenalectomies and one bilateral adrenalectomy were performed with the help of telementoring. All cases were performed by an expert surgeon, who was skilled in laparoscopic procedure but had no experience in laparoscopic adrenalectomy. All the procedures were successfully performed in a telementored fashion.

On 8 April 1997, the first intercontinental teleoperation was performed between the United States and Europe [4]. Laparoscopic adrenalectomy for a left aldosterone producing adenoma was performed on a 57-year-old man in Austria, while the telementor at Baltimore, Maryland, steered the laparoscope through robot and provided necessary instructions to the operating surgeon at Austria who could complete the procedure in a shorter time. During the operation, the laparoscope was exclusively manipulated from the remote site by an AESOP robotic arm.

We had reported a case of successful removal of parathyroid tumor via telementoring after the patient already had two unsuccessful surgical explorations for the condition of primary hyperparathyroidism (PHPT). A 20-year-old male patient was explored for PHPT in 2001 at Amrita Institute of Medical Sciences (AIMS), Kochi, India, but two successive explorations in the neck failed to reveal the adenoma in spite of preoperative image localization. The patient de-
teriorated due to persistent PHPT resulting in progression of disease leading to crippling state. SGPGIMS, Lucknow, and AIMS, Kochi, which are located 2,500 km apart, regularly have case discussions through telemedicine tool, using satellite communication provided by the Indian Space Research Organization (ISRO). In one of these sessions, the management of this problematic case was discussed, and it was mutually decided to have the operation by the same group of surgeons under the guidance of experienced senior surgeon at SGPGIMS through telemedicine tool. Re-exploration was done in this telementoring session with successful outcome [10].

12.3 Education and Training

The advancements in surgery over the years have seen integration of newer technologies in the surgical practice. Laparoscopic surgery, robotics, and telemedicine and its applications like tele-education, tele-consultation, and telementoring have revolutionized medical field [7, 12]. These technologies have received priority in the field of surgical education, knowledge sharing, and skill development, apart from the use in patient care and technology, which has been receiving importance in the healthcare system of many countries. Telemedicine has found its application in all branches of medicine. Teleradiology is the most common application, followed by cardiology, dermatology, psychiatry, emergency medicine, home health care, pathology, and oncology [18].

Telemedicine was initially used in laparoscopic surgical training [8], since the minimally invasive surgical technique needed continuous mentoring of the trained surgeons. DeBakey in 1965 transmitted guidance on open-heart surgery from the United States to surgeons in Europe over a broadband satellite [3]. Rosser et al. described early attempt at telementoring [15]. They developed a curriculum that begins with laparoscopic training course at Yale University and then continues in the local hospital operating room, where the surgeon’s performance is telementored. These initial studies established the safety and feasibility of telementored procedures. Sebajang et al. reported telementoring of 19 cases of advanced laparoscopic general surgical procedures performed by four community surgeons using telementoring. Each surgeon was telementored by an expert surgeon from a tertiary care hospital [16]. Thus, telementoring had a definite role in skill acquisition and enhancement.

For the continuous mentoring and reinforcement of endocrine surgical training, various modules can be used apart from intraoperative mentoring, e.g. tele-consultation, teleradiology, telepathology, tele-education, tele-CMEs and workshops. These modules help in the knowledge sharing and surgical skill acquisition, which the trainees received in a mentored fashion using tele-
medicine technology. Bruschi et al. [1], who had telementored adrenalectomies, found that telementoring is a viable method that can potentially add to surgical education and decrease the likelihood of complications due to inexperience with new techniques.

We at SGPGIMS are trying to add a different dimension to the concept of telementoring by also using telementoring as a tool in subspecialty growth in general and in reinforcing the endocrine surgical training. This hypothesis is based on the local needs of creating a critical mass of competent endocrine surgeons [9]. At present, there are few available expert endocrine surgeons in our country, though we have a vast patient load. We at SGPGIMS are using the telemedicine-aided technology to further reinforce the knowledge and skills of the short-course trainees who attend the endocrine surgical training program at our hospital for varying periods of 1–3 months. This group of trainees are selected on the basis of their experience in general surgery, aptitude in endocrine surgery, and the potential to pursue it with special interest while working in the same general department of large community hospitals and medical colleges. We have been successful in this endeavor by training two general surgeons with 10 years of general surgical experience in endocrine surgery. During a short training of 3 months, they had rotation in clinical and laboratory services and attended all the academic sessions conducted by the department. Following their return to their parent institute, continuous telementoring was used to monitor their endocrine surgical practice and to guide them to sort out diagnostic problems, in treatment planning and postoperative care, as and when required. Besides this, the trainees also received mentoring from the experts in associated specialties like nuclear medicine, endocrine pathology, and interventional radiology.

### 12.4 Future Directions

With advancement of modern telecommunication technology associated with its wider availability and decreasing costs, and easy availability of telemedicine-based gadgets, many centers around the world are practicing telementoring in the field of endocrine surgery. The next-generation Internet holds a great deal of promise to overcome the difficulties encountered in telementoring using current Internet technology. However, there are several issues related to application of telemedicine into surgical practice like licensure. Is it necessary that the remotely placed surgeon should also be registered with the state with which he/she is involved in telementoring? The American College of Radiology states that for teleradiology the physician must be registered in both the state of his/her residence and the state from which the image originates [18].
Such laws may come up for telementoring, since there is an issue of addressing the complications that may result due to the telementored procedures.

Many more centers are expected to use telementoring in surgery not only for performing advanced complicated endocrine surgical cases with expert guidance, but also for using it for patient care-related activities like preoperative treatment planning in difficult cases and postoperative care of complex surgical issues with mentoring from remote location. The legal issues of complications arising out of these telementored procedures have to be addressed.

**Summary**

- Remote mentoring through telemedicine technology is a feasible option to supplement skill and knowledge of an endocrine surgeon practicing at a distance.
- Global experience in telementoring in endocrine surgery is limited at present.
- It has a potential in the overall development of upcoming subspecialty like endocrine surgery.
- Setting up telementoring facility is feasible even in developing countries.

**References**

Training in Telesurgery: Building a Successful Program


13.1 Introduction

Over past years surgeons have sought methods to develop new operations; however, much advancement has been limited by the lack of facilitating technology and effective training. In the case of endoscopic and telemanipulative training, surgical training of both senior surgeons and resident surgeons proceeded without prior procedure development or detailed curricula. Clinical training for new techniques involving innovation often was at the expense of good surgical results. Bonchek, Ullyot, Lytle, and Cooley have cautioned surgeons who attempt new techniques and veer from established approaches [1, 8, 16].

Our goal in developing robotic and telesurgery procedures, as well as, training surgeons to do these procedures safely has been predicated on the same quality expected from conventional operations. We have done this through a progressive approach to each successive level followed by technologic “acclimatization.” After mastering each step and gaining experience with techniques and technology, we then move to the next level of surgical telemanipulation [3–5, 9, 10]. To expand the field of telesurgery, telemanipulative procedures were developed at East Carolina University (ECU), and objective-based curricula (Table 13.1) were designed to optimize both surgeon and team training. Team training is necessary to attain the best clinical results.

13.2 Methods

13.2.1 Telemanipulative Instrumentation

The da Vinci Surgical System (Intuitive Surgical, Sunnyvale, Calif.) is the telesurgery or “robotic” system currently available and has three components: surgeon’s console, patient side cart, and vision system. The surgeon’s console
### Table 13.1. Telesurgery and robotic surgical training, objective-based curriculum levels

#### I. System training

A. Didactic overview
   - Understand three-dimensional vision and electronics
   - Understand robotic instrumentation

B. Inanimate laboratory
   - Master robotic operative cart (draping and setup)
   - Master operative console
   - Master instrument and camera control

C. Animal laboratory
   - Console surgeon
     - Suturing
     - Tissue cutting
   - Patient-side assistant
     - Instrument exchanges
     - Camera cleaning
     - Clip application
     - Retraction
     - Trocar positioning

D. Cadaver laboratory
   - Master trocar positioning
   - Apply above to human anatomy
   - Apply above to variable body habitus

#### II. Advanced procedure specific training

A. Operative observation
   - Observe interaction with adjunctive surgical technology
   - Discuss training objectives with trainer and team
   - Patient positioning
   - Procedure steps
   - Port placement
   - Pearls and pitfalls

B. Didactic review

C. Inanimate models
   - Procedure steps
   - Apply all of the above

D. Cadaver laboratory
   - Master all of above
   - Apply to variable body habitus
provides ergonometic comfort via an interface through which the surgeon becomes totally immersed in the operative field (Fig. 13.1). This is accomplished by 10–15x three-dimensional digital stereotactic vision system. Furthermore, the computerized portion of the console allows for tremor filtration and the ability to scale one’s movements to perfect intricate movements. Console foot pedals control both camera orientation and focus. A foot pedal clutching mechanism allows immediate repositioning of instruments, allowing safe instrument excursions. The patient side cart positions and drives the wrist-like devices, while an assistant adjusts and performs instrument exchanges. Robotic arms and “wrist” instruments are placed through ports (8 mm) and converge in the operative field. Seven degrees of motion freedom are provided by the combination of trocar-positioned arms (insertion, pitch, and yaw) and articulated instrument wrists (yaw, pitch, roll, and grip). With experience, surgeons develop visual tactility and proprioception, even though tactile (haptic) feedback remains attenuated. The combination of the three components allows “eye-hand-foot” interactions, providing the surgeon with the necessary tools to perfect the necessary movements.

Fig. 13.1. The surgeon is immersed in the operative field facilitated by placing his or her head into the console, providing three-dimensional vision. Fingertips are placed in Velcro finger traps, which emulate movements made by the surgeon.
We have three *da Vinci* Surgical Systems including two standard four-arm systems and, most recent, the new *da Vinci S* System. Early on, only standard three-arm systems were available. After further engineering developments, a fourth arm was added to each three-arm system. This allows the surgeon more control over the operative field and enables one to assist him or herself. The *da Vinci S* System is slightly smaller and easier to use from both the surgical console and the patient side. Robotic instruments are longer and controls telescope allowing improved access in cardiac chambers and body cavities. The surgical cart is motorized, allowing more efficient docking. Improved software allows for faster surgeon interface with the computerized functions of system.

13.2.2

**Telesurgery Program Development**

In developing our robotic and telemanipulative surgery program, we have had both exhilarating and disappointing experiences. We have trained many surgeons worldwide and preceptored them when they return to their institutions. Our program has focused on training cardiac, gynecologic, urologic, and general surgeons. More recently, general thoracic surgeons and vascular surgeons have initiated training. We have helped to develop programs to the point that many programs are now teaching others. With each successful program, there has been a constant theme of “Team and Commitment.” We suggest following a definitive plan using an objective-based curriculum when learning these highly specialized and technical operations. Clearly, these operations are a team “activity,” and each member must play his or her part as an expert.

Before beginning actual training, one should review the literature and critically analyze the data to feel comfortable in advocating this approach for patients. If the surgeon truly does not believe that these procedures will benefit his or her patients, then traditional methods should be retained. Moreover, it is important to educate the operating room staff as to the difference in this modality and traditional surgery. Without operating room environment support including nursing staff and anesthesiologist, most surgeons will revert to traditional methods even after a few successful robotic or telemanipulative cases. The mission and purpose for developing a telesurgical program must be defined by both hospital administrators and surgeons. The real reason for using this new technology in minimally invasive surgery must be evaluated. Institutional commitments become much more solid when a surgeon organizes the program and development is not just for marketing reasons. The main goal should be to facilitate minimally invasive operations and maximize on its benefits, including faster patient recovery and an increase in patient volume. In other situations, the institution purchases a telesurgical system and then encourages use by the surgical teams. The later instance requires more work to
develop an understanding between hospital administrators and surgical teams. The potential is greatest when the surgical team and the hospital administration work together for improved patient care and institutional advancement.

A multidisciplinary approach is preferred and provides greater opportunity for collaborative work. In academic institutions, the intellectual process associated with a telesurgical and robotic program can promote grant writing and scientific publishing. Within all institutions, whether academic or not, regularly scheduled interest group meetings for faculty, staff, trainees, and students are important to maintain focus. Working groups should be instrumental in developing credentialing documents for their institution. New programs may be developed within these working interest groups, and realistic timelines should be enforced. Moreover, it is important for programs to provide educational programs within the community. We refer to this type of work as “outreach” and believe that it is important to enlist community support and provide education locally.

13.2.3 Surgical Training Curriculum

Team training is the most important early step. A carefully planned protocol or objective-based curriculum should be followed for best results. In the beginning of robotic cardiac surgery, the US Food and Drug Administration mandated that comprehensive training be provided for all institutional teams and surgeons planning to use the da Vinci surgical system. Our institution initiated this training program after our first clinical procedures were determined to be safe, efficacious, and facilitating. Objective-based and hands-on training was initiated in 2000 to provide a uniform start for early adopters of telesurgery technology. Each surgical team is trained intensively with many hands-on sessions for either 1 or 2 days, depending on the individual needs of each group. Most international groups train for several programs simultaneously; therefore, the program is most often for 4 or 5 days. Surgical teams usually consists of two surgeons (operating console and patient-side assistant) and two to three operating room staff, including nurses and/or scrub assistants. In addition, cardiac teams include a senior perfusionist and anesthesiologist [7].

Recently, the training program has been modified to include “basic system” training, followed by “advanced procedure” training. During the basic system training program, teams learn and demonstrate safe use of the equipment. After successfully completing more simple cases at their institution, they return for advanced procedure training, where more complex techniques are focused upon. In both programs, curriculum objectives are (1) to compare telesurgical and robotic methods to prior training and clinical experiences; (2) to understand and master surgical robotic technology, including both electronic and
mechanical components; (3) to be able to troubleshoot all parts of the system as well as resolve instrument arm conflicts; (4) to master surgical telemanipulation as applied to specific operations; and (5) to become both an accomplished console-based robotic surgeon and a facile patient-side assistant.

Team curriculum objectives are similar but focus more on sterile draping, operating room arrangement, instrument care, and device maintenance. As mentioned previously, basic system training includes didactic instruction and hands-on work for system setup, sterile draping, and both electrical and mechanical troubleshooting and emergency shutdown maneuvers. Teams return to their home institutions and concentrate on specific procedures to reinforce objectives learned and experience early success. After mastering these objectives, teams return for advanced training, including didactic sessions, an inanimate laboratory, animate procedures where appropriate, and fresh-cadaver training. We have found that objectives are reinforced when training is surgeon led, facilitated by a training specialist, and followed by an operative case. This allows surgical teams to experience interactions among team members in a dynamic “live-case” situation. Team members observe and are able to ask questions, while procedures are being performed. Permission from patients is necessary for this level of team participation.

13.3 Results

The initiation of training was in August 2000. Since that time (6 years), 228 teams have been trained at our training facility (Table 13.2). Teams include many surgical specialties including cardiac surgery (n = 129), general surgery (n = 32), gynecologic surgery (n = 24), urologic surgery (n = 33), vascular surgery (n = 4), and others (n = 6) (Tables 13.3, 13.4). As previously discussed, teams consist of surgeons, nurses, physician assistants, and scrub technicians. In addition, successful implementation of a robotic and telesurgery program in cardiac surgery also includes training of anesthesiologists and senior perfusionists. All training is approached in a step-wise manner, and each step is mastered before moving to the next level of complexity. This is most evident in cardiac surgery. Surgical teams first learn safe operation of the system, while doing less complex procedures such as internal mammary artery harvest and epicardial left ventricular lead placement for resynchronization therapy in select patients with congestive heart failure. It is not that these procedures are less important than intracardiac procedures, but they demand less complexity in the operating room. For instance, alternative cardiopulmonary bypass techniques usually are not required, and the heart is not arrested during these more simple procedures. Intracardiac procedures such as mitral valve repair and atrial sep-
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Table 13.2. Totals for training program

<table>
<thead>
<tr>
<th>Teams</th>
<th>Surgeons</th>
<th>Nurses</th>
<th>PAs and others</th>
</tr>
</thead>
<tbody>
<tr>
<td>All disciplines</td>
<td>228</td>
<td>482</td>
<td>259</td>
</tr>
</tbody>
</table>

aPhysician assistants  
bAnesthesiologists, perfusionists, and scrub technicians

Table 13.3. Cardiac surgery training

<table>
<thead>
<tr>
<th>Teams</th>
<th>Surgeons</th>
<th>Nurses</th>
<th>PAs and others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cardiac</td>
<td>129</td>
<td>270</td>
<td>190</td>
</tr>
<tr>
<td>System/IMAa</td>
<td>51</td>
<td>99</td>
<td>65</td>
</tr>
<tr>
<td>MV repairb</td>
<td>78</td>
<td>171</td>
<td>125</td>
</tr>
</tbody>
</table>

aSystem training and internal mammary artery harvest training  
bMitral valve repair training

Table 13.4. Surgery specialty training

<table>
<thead>
<tr>
<th>Teams</th>
<th>Surgeons</th>
<th>Nurses</th>
<th>PAs and others</th>
</tr>
</thead>
<tbody>
<tr>
<td>General surgery</td>
<td>32</td>
<td>62</td>
<td>17</td>
</tr>
<tr>
<td>Gynecology</td>
<td>51</td>
<td>41</td>
<td>14</td>
</tr>
<tr>
<td>Urology</td>
<td>33</td>
<td>58</td>
<td>28</td>
</tr>
<tr>
<td>Vascular</td>
<td>4</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Other</td>
<td>6</td>
<td>39</td>
<td>2</td>
</tr>
</tbody>
</table>

aSystem training and internal mammary artery harvest training  
bMitral valve repair training

tal defect closure require cardiopulmonary bypass and cardiac arrest. In addition, during these latter procedures, attention to operative times becomes more important. We have trained 51 teams, including 99 surgeons for system training, and many of those teams and surgeons have returned for advanced training including mitral valve repairs (78 and 171, respectively) (Table 13.3).
All teams trained have completed successful clinical procedures in their institutions with the telesurgical system. To date, quantitative metric evaluation of operative dexterity and efficiency has not been possible; however, proctor observation and self-testing suggest that each previously experienced surgeon gained significant knowledge and would be able to use the device in clinical cases competently. Operative team education directed towards technologic cohesion is perhaps the most important aspect of the training, and each team is very “able” by the end of the course.

13.4 Discussion

The widespread acceptance of endoscopic general surgery was attributed to independent work by Mouret, DuBois, and Reddick, who performed the first laparoscopic general surgery procedures in the mid-1980s. Despite early skeptics, procedures such as laparoscopic cholecystectomies ultimately became the gold standard [15, 21, 23].

Similar activities occurred in both gynecologic and orthopedic surgery. Currently, advanced laparoscopic surgery has become the mainstay of most intra-abdominal surgical practices. More recently, Mohr, Vanerman, Reichenspurner, and Chitwood have successfully used assisted vision in cardiac surgery procedures and have demonstrated excellent results when repairing complex mitral valve lesions [6, 19, 22, 24]. The limitations of two-dimensional endoscopy, fulcrum effect, and long, motion-amplifying instruments have dampened the enthusiasm of many cardiac surgeons for endorsing video-assisted operations. Early on, we held training courses for video-assisted mitral valve procedures and noted a low rate of adoption. This changed upon initiation of training, using robot-assisted systems with three-dimensional vision. Recent publications project that surgical vision and training systems will enable modeling of most surgical procedures through immersive technology. They suggest the probability of developing training systems that can emulate hemorrhage, skin turgor, and more tactile sensations [11–13, 17, 18]. Visual cues provide over 70% of human sensory input, optical magnification and high-resolution cameras provide compensation for haptic loss and offer “visual tactility” [18]. With three-dimensional cameras, many obstacles present with traditional endoscopic surgery can be avoided, including image inversion and tremor amplification.

The optimal approach for early and long-term success includes a structured plan for program development including procedure development and careful training. Furthermore, a multispecialty telesurgical and robotic program offers specialty cross-pollinations in training and procedure development. Just as in all aspects of education, an objective-based curriculum structured for learn-
ers to master the details of telesurgical and telemanipulative systems facilitates success. Regarding program development, surgeons who are technically facile and experienced in traditional techniques should be selected. Resident surgeons and clinical instructors are included in our training program and start as patient-side assistants but soon move to the console. In general surgery, resident surgeons start with less complex cases like cholecystectomies [2, 14, 20]. In cardiac surgery, after mastering patient-side assistance and troubleshooting, our clinical instructors move to the console and begin with the annuloplasty portion of a mitral valve repair. They also become very facile in internal mammary artery harvesting with times of 40 min after approximately 15 cases. This is comparable to harvesting the internal mammary artery in a conventional sternotomy case.

We believe that with proper academic training, the same or better-quality operations may be done with these new computer-assisted and telesurgical systems. Virtual operations, radiographic instrument positioning, and navigation systems may be the next technology to be added to the current systems. This would allow for improved placement of ports and cameras, with increasing accuracy. Development of smaller instruments and access ports, coupled with telescopic “end-chip” three-dimensional cameras, may carry surgeons to the next step towards fully integrated telesurgery procedures.

**Summary**

- Team training is the most important early step in a robotic and telesurgery training program.
- Teams consist of surgeons, nurses, physician assistants, and scrub technicians and also anesthesiologists and senior perfusionists.
- The modified training program includes basic system training, followed by advanced procedure training.

**References**

Telesurgery and the Law

Neera Bhatia

14.1 Introduction

Although telesurgery has developed productively and generated major and often revolutionary changes in the way healthcare is delivered, however, as is often the case, the legal and regulatory environment has not kept pace with the technology.

There are a number of issues that arise within medical law and its common application to everyday situations; the use of more technological methods of treatment that are often perplexing requires lengthy consideration by judges and academics in medical law and ethics.

14.2 Licensure

One issue is whether the network itself needs to be licensed. One goal of a licensure requirement is ensuring that facilities meet minimum quality standards. Historically, hospitals have received licensure for their facilities with the state of operation. Would a healthcare system, then, be required to possess a license from the state in which it has a “virtual” facility? It is likely that states may require some form of licensure or other assurances of minimum technological standards (such as the minimum resolution of network-transmitted images).

The question of licensure also becomes an issue to the individual telesurgery practitioner. Is it necessary to obtain a license in another state where telesurgery consultations are performed? The consulting physician is not the only one at risk. A licensed physician who aids a non-licensed physician in practicing medicine may also face civil fines, suspensions, or revocation of his or her medical license.
14.3  
**Accreditation**

Federal regulations, state law, and private accrediting standards require hospitals to adequately credential providers and to ensure that medical staff members are competent in their practice areas. Do hospital-based telesurgery networks focus attention on, and draft medical staff bylaw changes to reflect telesurgery proficiency? Do remote physicians be admitted to the host’s medical staff? If so, does this then impose upon the host a duty to continuously monitor remote physicians’ competence and skill to the same degree as it does with other staff members? No clear answers emerge.

Further, practitioners who use the new technologies must upgrade their skills appropriately. Failure to correctly calibrate an instrument can increase the likelihood of inaccurate diagnosis. Deficiencies or failures in equipment used to transmit an image, video clip, or patient record may increase liability. In addition, the potential to recover large award from telecommunication companies and manufacturers may create incentives to bring suit against all of those involved in a telesurgery consultation.

14.4  
**Privacy**

Telesurgery does not change the duty of confidentiality and the fundamental privacy issues involved, but it does raise the concern that patients may be unaware of the extent to which their medical information may be disclosed to others. Virtually, any telesurgery consultation involves electronic transfer of patient medical records and information. Patient privacy must be a major consideration in the development of information systems.

Currently, medical privacy regulations normally do not contain specific technical requirements. Some states like California attempt to deal with the privacy issue by requiring patients to give informed consent to healthcare delivery via telesurgery. Will consenting patients fully appreciate the consequences of having their examinations electronically communicated to numbers of people they cannot see, including technical support people as well as health-care professionals?

Some of the pitfalls surrounding electronic patient records can be avoided by establishing and enforcing strict protocols that are clearly understood by staff. These guidelines are not, in and of themselves, enough protection. Even though no security system for information will be completely immune from discontented insiders or determined hackers, health information managers should implement a system that ensures high levels of clinical access and util-
ity, while maintaining secure and confidential patient information [7]. Techni-
cal safeguards, as well as administrative and procedural methodologies, should
be established.

14.5 Malpractice Liability

Healthcare systems owe a duty to patients in their facilities to prevent harm
negligently caused by them, their employees, and agents. The law has devel-
oped to where healthcare systems must adequately supervise and credential
their staff and independent physicians, providing services under their auspic-
es. Traditionally, in medical negligence cases, the onus is on the patient, being
the claimant, to prove that the doctor, being the defendant, formed a relation-
ship with that patient, much like the signing of a contract, and consequently the
doctor owes a duty of care toward that patient. The patient must then prove that
the doctor breached this duty of care by failing to conform to the accepted stan-
dard of care, which directly caused or led to cause detriment to the patient.

Legal parameters for medical malpractice are the same whether the claim
relates to telesurgery or other technologies. First, it must be determined that a
physician-patient relationship existed. If so, the issue of whether the physician
breached his or her duty of care must be addressed. A physician-patient rela-
tionship may arise out of an expressed or an implied agreement. Generally, the
courts have found that provision of medical care creates that relationship, even
in the absence of reimbursement. Most telemedical consultations would likely
be viewed as establishing the requisite physician-patient relationship. Accord-
ingly, practitioners wishing to limit involvement in a case should define the
limits of their participation to the patient up front. Such consent should be in
writing and retained by the consulting physician.

English law requires that healthcare professionals exercise reasonable care
in the performance of their particular skills. In medical malpractice claims, the
standard of care, which is applied to all healthcare professionals and to all as-
pects of healthcare practice, was established in the case of Bolam v. Friern Hos-
pital Management Committee in which Justice McNair stated [1]: “A doctor is
not guilty of negligence if he has acted in accordance with a practice accepted
as proper by a responsible body of medical men skilled in that particular art.”

The essence of the “Bolam test” is that professionals are to be judged against
the standards of their peers. This means that it is unlikely that they will be
found negligent if the experts from their profession who are called on to give
evidence are prepared to accept that the defendant’s actions were proper.

This may well be problematic as telesurgery is not a widespread practice;
therefore, other medical practitioners may not be in a position to agree or sup-
port the negligent doctor’s use of a particular operating technique, using a robotic device as an accepted practice.

A surgeon who does not perform a hands-on examination but does so using high-tech robotic machinery could be regarded as delivering less-than-adequate care. If compressed digital images are not reconstructed well, causing loss of valuable diagnostic information, a doctor could possibly face difficulty in diagnosis, which could consequently cause the patient further detriment, possibly even death.

It would seem that in order to limit or control ambiguity when measuring the standard of care that is owed to patients in one country to another would be to create a global standard of care that is then used to establish medical negligence or malpractice. It would be markedly valuable for both legal and medical practitioners to have a uniform set of principles or rules that govern the way in which claims of medical negligence are dealt with.

Most professional associations or governing bodies have yet to devise strategic guidelines or a universal set of standards that should be followed after the unfortunate occurrence of a medical blunder using telesurgery. Regulatory authorities seem to be in a similar position and have not devised or adjusted procedures in establishing and resolving medical negligence claims, in accordance with the ever-evolving innovations in delivering healthcare in the 21st century.

Some believe that use of these technologies will lower liability, since telesurgery consults involve two practitioners working together, resulting in more comprehensive care leading to better patient outcomes. Alternatively, as technology increases in sophistication, so does patient expectation.

Unlike other medical technologies, many of the tools involved in telesurgery consultations were developed for non-medical purposes [6]. Even telesurgery experts disagree about optimum technical specifications for compression, resolution, and matrix size. Finally, because even state-of-the-art technology quickly becomes outdated, it is unclear what obligations practitioners have to upgrade their systems.

Technical issues do not present only legal considerations. The appropriateness of using telesurgery in a particular setting might also be argued [4]. Allowing non-physicians to participate in a telemedical consult, or to use a medical database to engage in electronic patient triage, presents other potentially contentious issue in the areas of informed consent and choice of laws.

The issues become murkier as telesurgery matures. For example, if remote robotic surgery is done through an interstate network or if telesurgery networks make physicians available to patients in the absence of physicians at the patient’s location, it seems clear that the physician who remotely diagnoses and treats patient’s interstate would be required to secure a patient’s informed consent to render care. The standards for when consent is “informed” vary by state.
To the extent that the standards conflict, which state’s standards apply? The answers to these questions often determine the outcome of medical malpractice litigation. Cases involving teleconsultation across state lines will raise classic choice of law’s issues [3]. Should the court apply the law of the state in which the patient lay on the examining table, or the state where the tele-expert viewed the patient?

Fundamental aspects of medical law and ethics are informed consent and the right for the patient to know and understand the risk involved in medical procedure or treatment. In the United States, informed consent varies from state to state; for instance in some states sufficient informed consent is what a reasonable patient would consider important; however, in other states, informed consent relies on what the prudent reasonable provider would consider necessary or sufficient.

In the case of *Lopez v. Aziz* [2], the court held that a telephone conversation between a primary care doctor and an obstetrician concerning a pre-eclampsia patient was insufficient to establish a doctor and patient relationship. The existence of a doctor and patient relationship is obscure where a doctor has only ever consulted with the other doctor (in the other country or state) and never with the patient. This clearly illustrates a shift away from the traditional relationship of trust and re-assurance that patients have with their doctors. It can be seen as a complete detachment from any form of contact with mankind, in the sense that there is never any formal meeting or conversation with a surgeon, and furthermore a patient is then also operated on by a machine as opposed to a human being.

**14.6 Conclusion**

Although telesurgery equipment and robotic devices can be considered as being state of the art, technology is continually changing and becomes outdated very quickly. In such instances, it would increase the burden on practitioners to keep updated on new technological equipment used in telesurgery, and the cost and legal obligations on practitioners to keep their systems updated is worth consideration for the future.

There is the need for protocols and universal compatibility of equipment, whereby when there are language barriers between practitioners in different countries, they are still both using the same equipment.

Although developed Western countries can reap the reward of telesurgery today and many underdeveloped countries can imagine the enormous benefits of remote surgery, it is somewhat let down by the lack of progression in other
fundamental needs of the 21st century, such as infrequent electricity supplies and poor telecommunication networks.

The challenges of robotic devices used in telesurgery do not just apply to underdeveloped countries; although the accuracy and efficiency of robotic devices have improved, there remain a number of obstacles that need to be overcome. Trauma surgeon Colonel John Holcomb was deployed to Iraq seven times and noted “...the lights still go out in operating rooms in Iraq, and communication is exquisitely difficult” [5].

Time delays in transmission, even as small as milliseconds, can lead to disastrous results in case of remote surgery and potentially several medical malpractice claims. Even using remote surgery, there is still the need for an anesthetist and another surgeon in the operating room in case of robotic malfunction or other technological disruptions, which would not occur when a traditional hands-on method of operating is applied.

The repercussion of technological failures in terms of medical malpractice claims is colossal. Due to the worldwide canvas that telesurgery covers with practitioners and surgeons across various continents, working together in an international operating theatre, there is the need for globalization of practice and procedures of telesurgery and the need for clear, coherent, and universal guidelines in preparation for potential legal and ethical challenges and debate.

National legislation is certainly necessary to clarify the vagueness stemming from inadequate federal and state laws. However, until such legislation is passed, those involved in the delivery of telesurgery must take what steps they can to ensure that personal records remain confidential and secure. Internal and external reviews of one’s existing and/or proposed recordkeeping methodologies, from both a legal and a technical perspective, are advisable. By showing that privacy controls and safeguards are being researched and implemented, one may lessen the opportunity for allegations of negligence or reckless disregard for privacy concerns.

**Summary**

- Although telesurgery has developed immensely, the legal and regulatory environment has not kept pace with the technology.
- Whether the network itself needs to be licensed is an issue of concern.
- Through privacy controls and safeguards, one may lessen the opportunity for allegations of negligence or reckless disregard for privacy concerns.
- Until some legislation is passed, clarifying the vagueness stemming from inadequate federal and state laws, those involved in the delivery of telesurgery must ensure that personal records remain confidential and secure.
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1. [1957] 1WLR 582, [1952] 2 All ER 118
Telesurgery: an Audit

Sajeesh Kumar

15.1 Telesurgery Is Still in Its Infancy

Since telesurgery is a relatively young medical technology, further long-term study with regard to patient advantages, cost-effectiveness, safety, and clinical applicability is required before the technology can be integrated into the healthcare system. As for standard robotic surgery (not telesurgery), the market is growing worldwide at an average rate of 25% annually, due, in large part, to the approval of new procedures such as single- and multi-vessel, closed-chest coronary artery bypass graft(s) (CABG) on a stopped heart, and single- and then multi-vessel closed-chest CABG on a beating heart.

In addition, given better acceptance in the general marketplace among surgeons, hospitals, and patients, this growth rate will likely to increase. It must be noted that the growth of robotic surgery will directly support and help the growth of telesurgery, because surgical robotics are, of course, an integral part of telesurgery.

15.2 Will Telesurgery Replace Traditional Methods?

Telesurgery promises to revolutionize healthcare and speed postoperation recovery. Yet, the technology requires a great deal of further development. One of the main drawbacks of existing surgical robots is the lack of tactile feedback. Surgeons using the joysticks do not actually “feel” the patient; they must rely on visual cues to judge tension. Haptics, defined as the ability to sense touch, will likely be a quality achieved by the next generation of surgical robots. Another challenge that telesurgery faces is maintaining a secure, continuous connection, with little or no delay in transmission. Major advances in technology are required before these connections can be implemented. The coming of telesurgery does not mean that surgeons can abandon traditional methods. Currently, when a surgeon is performing a telesurgery procedure on a patient at a
distance, there would need to be an individual at the scene who is competent to convert to an open procedure should things go wrong. As well, the economics of telesurgery must be further analyzed. Institutions must ensure that the cost of telesurgery does not exceed the traditional expenses involved with transporting patients and surgeons.

### 15.3 Economics of Telesurgery

Today, the surgical robot – the *da Vinci* system – has barely penetrated the market. The robotic-assisted procedure performed most frequently, laparoscopic radical prostatectomy (LRP), accounts for little more than 1% of all radical prostatectomies. Analysts forecast that the worldwide market for all robotic procedures will grow at an annual rate of 25% until 2009. Beyond 2009, it is estimated that the market will grow by 30–45% annually until 2025, due to two main reasons: (1) systems will improve in ease of use and features, and (2) new players will enter the market, as the opportunity grows and as medical robotics generally becomes more established in health care.

As described earlier in Chap. 1, on 7 September 2001, a modified ZEUS system was used to prove the technical feasibility of telesurgery. Dr. Jacques Mariescaux in New York performed a laparoscopic cholecystectomy, while his patient was 4,000 miles away in Strasbourg, France. The operation took less than an hour to complete and was hailed as the medical breakthrough of the year. Though technically feasible, however, this was not an indication of how surgical care would be delivered for two reasons: (1) the private asynchronous transfer mode (ATM) telecommunication link used was too expensive for everyday use, and (2) it makes sense to have a qualified surgeon next to the patient where possible.

However, the next phase was both clinically and financially much more realistic. On 28 February 2003, Dr. Anvari of Hamilton, Ontario, Canada, participated in two back-to-back laparoscopic Nissen procedures, assisting and guiding the local surgeon, Dr. McKinley, who was 250 miles away in North Bay, Ontario. Dr. Anvari had performed more than 1,500 such procedures, and Dr. McKinley, though a skilled laparoscopic surgeon, had performed less than 100. During the operations, Dr. Anvari routinely pointed out proper angles of approach, needle placement while suturing, hidden clues, and other intricacies that only can be seen by the eyes of an expert. It was at this point that it became obvious that telesurgery is an extremely valuable tool, not in the distant future, but today. Furthermore, though Dr. McKinley performed most of the procedure, the procedure time was comparable to an expert surgeon’s time (the first case took less than an hour, and the second case took about 90 min to
complete). Dr. McKinley learned from Dr. Anvari’s experience hands on, and, most importantly, the patient received the best quality of care without leaving her hometown. In addition, the financial feasibility was enhanced because an affordable and readily available public multiprotocol label switching (MPLS) telecommunication network was used. Between February 2003 and December 2003, Dr. Anvari and Dr. McKinley performed more than 20 such procedures, from Nissen fundoplications to hernia repairs and bowel resections. These demonstrations showed that providing state-of-the-art expert care could be economically feasible in the underserved rural areas. None is as complicated as brain or heart surgeries, but every time a surgeon conducts a successful telesurgery, he/she reinforcing the point that telesurgery is possible.

With telesurgery, the expert surgeon does not travel to where the patient is located and therefore does not reduce effective surgical days, thereby allowing him/her to use his/her time more efficiently and reduce the cost of the procedure. In addition, patients and their families do not travel to the expert surgeon and patients can heal at home. Finally, the rural surgeon will learn from the expert surgeon and improve with each procedure, as he/she will perform more complicated procedures in his/her local operating room, procedures that in other circumstances would go to the experts. This latter point helps with attracting young, less experienced surgeons to these rural areas and with their continued training/education and retention in these areas.

15.4 Issues Related to Telesurgery: a Brief Overview

Immediate or widespread implementation of telesurgery is hindered by many factors. Issues related to telesurgery may include lack of telecommunication infrastructure, affordability of programs, cost of the equipments, accuracy of the medical and non-medical devices used, training of personnel involved, lack of guidelines and protocols, sustainability of the projects, reimbursement for telesurgery consultations, regulations regarding sharing of information, legal liability, privacy, and security.

Financial planning for telesurgery should include the costs of telecommunication and information technology infrastructure and medical devices, as well as costs such as personnel training, monthly network access fees, maintenance, telephone bills, and other operational expenses.

Once the objectives of a program are identified, technology support personnel should be consulted to clarify technical equipment specifications and facility requirements. Protocols and guidelines must be developed, which will provide clear direction on how to utilize telesurgery most effectively. The training of remote operators is especially critical in telesurgery. The reliability of a pro-
gram is also related to the surgeons’ experience with telesurgery technology, and his/her awareness of its limitations.

Many nations do not have explicit policies to pay for telesurgery services. A major telesurgery payment policy is crucial. Existing liability laws and reimbursement structures also frustrate the growth of telesurgery. The prototype ZEUS telesurgery system was used in Canada primarily because it was able to more readily receive regulatory clearance for the study there. In addition, because it is a large country with a sparse population, Canada and Australia are best suited for a trial of telesurgical systems. Australian government spends millions of Australian dollars each year transporting patients to expert medical centers. Each patient requiring transportation uses chartered flights or Royal Flying Doctor Service, and, depending on the procedure, the government also pays for the travel costs incurred by the patient’s family.

Meanwhile, several telemedicine services are being integrated to regular healthcare systems in the United States and the Scandinavian countries with reimbursement/payment options. Studies should be conducted to implement, monitor, evaluate, and refine the telesurgery payment process. Additionally, it should be noted that telesurgery licensure and indemnity laws might also need to be formulated. This issue, however, remains a cloudy region for healthcare strategists and has implications for surgeons and rural/remote practitioners who practice across state or country lines.

It is observed that successful telesurgery programs are often the product of careful planning, sound management, dedicated professionals, and support staff, and a commitment to appropriate funding to support capital purchases and on-going operations. It reflects a commitment to teamwork to link technical and operational complexities into a fully integrated and efficiently functioning program. Telesurgery service providers, health insurance agencies, and all concerned institutions should convene to lead a workable model for telesurgery service improvements. The professional communities should bring out telesurgery service guidelines, which would pave the way for consensus on several difficult issues, including technical and service standardization for telesurgery.

Though the accuracy and efficiency of robotic controls have improved tremendously, several technological hurdles need to be cleared before robotic telesurgeries become a mainstay in medicine. The issues of latency (the delay in the transmission of what happens at one end and what happens at the other end) and jitter (the interrupted transmission of the electronic signal) can make the difference between a successful and disastrous operation.

Meanwhile, the initiative to make surgical robots smaller and lighter has already begun, in part because the US National Aeronautics and Space Administration (NASA) is exploring telesurgery for its use in remote locations, like space. In 2005, an astronaut in NASA’s Aquarius Underwater Laboratory in
the Gulf of Mexico was telementored – essentially, coached via video and audio links – by Dr. Anvari, in the art of suturing and other surgical tasks.

### 15.5 An Outlook

The public demand for quality surgical care including the availability of the latest techniques will become the major surgical problem in the coming years. In addition, advances are introduced at breakneck speed with the “latest” replaced a year later with something better. The future of telesurgery will include a series of advanced technologies that will combine to improve the quality of surgical care, including preoperative imaging (i.e., CT scan), surgical simulation for training, real-time intraoperative image guidance (e.g. three-dimensional ultrasound), and force reflection and feedback.

Beyond 2020, a patient with a clogged left anterior descending (LAD) artery needing bypass surgery will be scanned 2 days prior to the minimally invasive procedure. The next day, the surgeon will practice the operation using the scan data, using simulation technology on the robot to determine port placement, angles of approach, and to learn patient-specific pathology. On the day of the operation, using preoperative data and real-time imaging, the LAD is identified using image superimposition (as is used in sports broadcasting today), with the blockage being highlighted. This is important, as it is difficult to identify the bypass location on a heart during minimally invasive surgery, due to a limited and magnified view of the heart.

Furthermore, the telerobot will prevent the surgeon from approaching the wrong coronary arteries or surrounding structures of the heart by limiting the workspace. Given the improvements in patient outcomes and surgeon efficiency provided by robotics, there can be no doubt that robotic surgery and telesurgery have a significant role to play in future medical care.

### 15.6 Conclusion

Healthcare providers are now looking at telesurgery as a model of improving, automating, and enhancing patient care. For those who hope to run and put together leading surgical centers for service, research, or teaching they must embrace telesurgery.

This book elaborates on many aspects of telesurgery. Authors have shown telesurgery to be practical, safe, and effective. Success often relates to the effi-
ciency and effectiveness of the transfer of information and translates into improved or enhanced patient care than would otherwise be possible.

Available telesurgery technology still has considerable room for improvement. However, the challenge is why, where, and how to implement which technology and at what costs. Asking the right questions will drive the technologies. A needs assessment is critical before implementing a telesurgery project. Sometimes, the technology drives the care model, rather than patient need taking precedence. Telesurgery as delineated in these pages may appear novel but is rapidly coming into common and mundane usage through multiple applications. Time alone will tell whether telesurgery (to paraphrase Neil Armstrong) is “one small step for Information and Communication Technology but one giant leap for surgical care.” However, from the pages of this first ever book on telesurgery, the future promises to be exciting. Optimistically, the journey toward improved patient care will be well worth the wait for those benefiting from these technologies.

Summary

- Telesurgery is a relatively new medical technology, hence requires further research before being integrated into the healthcare system.
- The economics of telesurgery must be analyzed to ensure that it is cost effective.
- The worldwide market for robotic/tele surgery procedures are expected to grow immensely over the coming years.
- Latency and jitter are important technical hurdles to be overcome in telesurgery.
- The future of telesurgery will include a series of advanced technologies that will combine to improve the quality of surgical care.

Bibliography

achalasia A disorder of the esophagus that affects the esophagus’s ability to move food toward the stomach.

AESOP A surgical robot capable of positioning an endoscope in response to a surgeon’s verbal commands. This allows the surgeon to have direct control over the endoscope in minimally invasive surgical procedures.

anaglyph A type of stereo three-dimensional image created from two photographs taken approximately 2.5 in. apart (the typical distance between human eyes).

augmented reality The idea that an observer’s experience of an environment can be augmented with computer-generated information. Usually this refers to a system in which computer graphics are overlaid onto a live video picture or projected onto a transparent screen, as in a head-up display.

brachytherapy A type of radiation therapy in which radioactive materials are placed in direct contact with the tissue being treated.

bronchoscopy Examination of the bronchi using a flexible, lighted tube called a bronchoscope.

cholangiography A study that examines the bile ducts with the aid of x-rays. These studies may be performed by multiple different techniques including ERCP, CT scan, ultrasound, and MRI.

colonoscopy A test to look into the rectum and colon through a long, flexible, narrow tube with a light and tiny lens on the end. This tube is called a colonoscope.
computer-assisted surgery  A technology of surgical simulation using three-dimensional organ models reconstructed medical imaging, by computer graphics technique.

*da Vinci Surgical System*  The *da Vinci* Surgical System consists of an ergonomically designed surgeon’s console, a patient-side cart with four interactive robotic arms, a high-performance vision system, and proprietary instruments. Powered by state-of-the-art robotic technology, the surgeon’s hand movements are scaled, filtered, and seamlessly translated into precise movements of the instruments. The net result: an intuitive interface with breakthrough surgical capabilities.

doscope  An illuminated optic instrument that is inserted through an incision.

EndoAssist  Intuitive camera control in endoscopic surgery.

gastroscopy  An examination of the inside of the stomach using a thin, lighted tube (called a gastroscope) passed through the mouth and esophagus.

haptic  Of or relating to the sense of touch.

Internet 2  A consortium of universities and industries, connected by a high-speed computer network, which seeks to develop next-generation Internet technologies.

LAN  A local area network (LAN) is a group of computers and associated devices that share a common communications line or wireless link.

laparoscopy  A surgical procedure performed through very small incisions in the abdomen, using specialized instruments. A pencil-thin instrument called a laparoscope is used, and it gives the surgeon an exceptionally clear view, on a TV monitor, of the inside of the abdominal cavity.

laparoscopic cholecystectomy  Laparoscopic cholecystectomy is the removal of the gallbladder, using small incisions in the abdomen. A telescope (laparoscope) is used to visualize the gallbladder so it can be dissected and removed through a small abdominal incision.

Lindbergh operation  The Lindbergh operation was named after American aviator Charles Lindbergh, because he was the first person to fly solo across the Atlantic. The Lindbergh operation had nothing to do with planes, but
rather was the first transatlantic telesurgery. It was the first time in medi-
cal history that a technical solution proved capable of reducing the time de-
lay inherent to long distance transmissions, thus making this type of pro-
cedure possible. This operation, involving a minimal-invasive surgery, was
performed using telecommunications solutions based on high-speed servic-
es and sophisticated surgical robotics.

**MPLS (multiprotocol label switching)** Enables administrators to define
routes known as label switched paths (LSPs) from one label edge router
(LER) to another, through a series of line service requests (LSRs), across the
MPLS network. These LSPs are pre-assigned and pre-engineered paths that
packets with a certain label should follow.

**minimally invasive surgery** Any technique involved in surgery that does
not require a large incision.

**olfaction** The sense of smell, or the action of smelling.

**Operation Lindbergh** See Lindbergh operation.

**remote surgery** See telesurgery.

**ROBODoc** ROBODoc is a documentation tool similar to JavaDoc. It is used
to extract API documentation from source code. It can be used with any
language that supports remarks and works by extracting specially format-
ted headers. These are then reformatted into HTML, DocBook, TROFF,
ASCII, LaTeX, PDF, or RTF.

**telemedicine** Use of telecommunications technology for medical diagnosis
and patient care when the provider and client are separated by distance.

**telementoring** The use of audio, video, and other telecommunications and
electronic information processing technologies to provide individual guid-
ance or instruction, for example, involving a consultant guiding a distant
clinician in a new medical procedure.

**telestration** The ability to draw on a television screen using a special stylus
pen; in surgery, telestration is useful as a teaching tool.

**telesurgery** Also known as remote surgery. It is the ability for a doctor to
perform surgery on a patient even though they are not physically in the
same location.
**urology**  A medical specialty that deals with disturbances of the urinary (male and female) and reproductive (male) organs.

**virtual reality**  An artificial environment created with computer hardware and software. To “enter” a virtual reality, a user wears special gloves, earphones, goggles, and/or full-body wiring. In addition to feeding sensory input to the user, the devices also monitor the user’s actions. The goggles, for example, track how the eyes move and respond accordingly by sending new video input.

**ZEUS Surgical System**  ZEUS is a minimally invasive robotic surgery system. ZEUS can be known as an RSS alternatively. ZEUS is known widely since it was used in a telesurgery operation where the surgeon was in New York and the patient was in France on 7 September 2000. (Zeus is the supreme deity in Greek mythology.)
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