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Telementoring and Telesurgery: Future or Fiction?

Vitor da Silva, Tom McGregor, Reiza Rayman, Patrick PW Luke
CSTAR, Department of Surgery and Biomedical Physics
The University of Western Ontario, Schulich School of Medicine
London, Ontario,
Canada

1. Introduction

Over the last two decades, minimally invasive surgery (MIS) has emerged as an attractive alternative to traditional open surgical procedures. MIS has been shown to provide excellent surgical outcomes with the added benefit of decreased procedure-related morbidity. Minimal bleeding, reduced blood transfusion rates, shorter hospitalization, and shorter recovery times are all proven advantages for laparoscopic procedures. [1-3] However, many MIS procedures are more technically challenging than the traditional open counterpart, and the learning curve to proficiency is markedly steeper than standard open procedures. Several factors including establishing adequate access, two dimensional vision, decreased depth perception, restricted instrument maneuverability, decreased dexterity and dampened tactile feedback are all unique limitations that make laparoscopic surgery challenging for surgeons trained in traditional open approaches. To the laparoscopically naïve surgeon, this translates into a loss of confidence in performing a procedure in which they were previously skilled. Appropriate training and education are therefore essential for a surgeon to develop the necessary skills required in order to comfortably perform a surgery adequately and safely. Unfortunately, resources are limited. Time, monetary and geographical constraints often limit the ubiquitous dissemination of new surgical knowledge, skills and techniques. The inability to provide adequate training opportunities and support for surgeons in the community continues to be the limiting factors determining the success and widespread availability of laparoscopic surgeries.

Thankfully, with the ever-increasing push to incorporate technological advances into the medical field, we are now able to overcome these barriers. In this chapter we outline how the recent progress in technology and telecommunication has led to the advent of telemedicine – an ingenious solution to our current problem, which will allow for the widespread availability of MIS and improve patient care.

2. What is telemedicine?

Defined as "medical care at a distance", telemedicine is a broad term referring to a physician's ability to practice medicine and directly influence patient care without being physically at the bedside. The underlying principle of telemedicine involves advanced

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telecommunication systems for data acquisition, processing and display allowing the physician or health care worker to transfer their expertise from a remote location. This opens the door for a wealth of applications, transcending geographical barriers when participating in patient care. Of particular interest to our discussion are the two main branches of telemedicine for surgeons – telementoring and telesurgery.

3. Telementoring

As cutting edge technology evolves, new surgical techniques are developed. This has occurred with the development of laparoscopy, laser, and robotic surgery. Surgeons already established in their community or academic practices have limited time to re-train or take sabbaticals to learn new skills necessary to carry out novel complex operative procedures. In part, this may have contributed to prolonged operative times and alarmingly high complication rates associated with the early development in laparoscopic radical prostatectomy (LRP) [4]. In general, the ability to efficiently train a surgeon to become facile at LRP has requires fellowship training, or recruitment of an experienced surgical mentor. However, when local expertise is not available, it is a challenge to recruit a mentor to teach novel operative techniques, as there rarely exists an established remunerative or academic reward to lure the mentors away from their regular patient-care and academic activities in order to travel and teach others. Therefore, telementoring has been developed to allow long-distance training utilizing mentors from a different hospital, city or continent.

Telementoring involves procedural guidance of one professional by another from a distance using telecommunications. This has involved interactions involving audio dialogue, video telestration (video tablet and pen), and even guidance of a camera or laparoscope with a surgical robot such as Aesop™ (Computer Motion, Santa Barbara, CA). In order to send audiovisual data, connections using WAN (wide area network), LAN (local area network), integrated services digital network (ISDN) or internet protocol (IP) links have been utilized. Security has been established through virtual private networks (VPNe) to prevent others to access and manipulate connections.

At first, telementoring was developed by surgeons from the Johns Hopkins University group utilizing rudimentary teleconferencing audiovisual equipment and a video sketch pad to provide telestration (Cody Sketchpad, Chryon Corp., Melville, NY). Trainees were provided mentorship from the staff surgeons situated 1000 feet away [5]. This developed into telementoring studies involving the USS Abraham Lincoln Aircraft Carrier Battle Group. Five laparoscopic inguinal hernia repairs were performed under telementored guidance from land-based surgeons from Maryland and California [6]. This established the ability to perform long-distance telementoring across bodies of water in times of war. Furthermore, Kavoussi's group utilized the Aesop™ robot as well as the Socrates telestration system (Intuitive Surgical) to telementor 17 urologic operations (including laparoscopic nephrectomy) between Baltimore, Maryland to Rome, Italy. However, the procedures were associated with a half second image delay between sites, and a high technical failure rate (5/17) due to an inability to establish connections through their 4 ISDN lines during times of heavy traffic [7;8].

In its early development, most of the procedures utilizing telementoring have required that an experienced surgeon was situated at the patient's operative tableside. Accordingly, in March 2003, our group from London, Ontario, Canada harnessed SOCRATES™ and AESOP™ telerobotic technology through 4 ISDN lines to successfully telementor laparoscopic nephrectomy and pyeloplasty with the mentor situated over 200 km away. Since our intent was to test the ISDN connections and the robotic platforms, we ensured that the bedside surgeon was equally as experienced as the mentor, and could complete the operation in case of communicative technical failure.

Subsequently, our group has prospectively tested telementoring in a 'real-world' situation, with a truly 'inexperienced' trainee with a 'complex' new procedure. As we have stated in the past, LRP is one of the most technically challenging operations in urology, with a steep learning curve associated with prolonged operative times, complications and poor oncologic outcomes during the early development of the procedure [4]. It has been stated that surgeons need to complete 50-300 cases in order to obtain operative proficiency for LRP. For the first time, we described the experience utilizing long-distance telementoring to facilitate the performance of the LRP with a trainee surgeon naïve to LRP. It should be mentioned, however, that although the trainee had never performed LRP, he had a high volume laparoscopic surgical practice. Utilizing an ISDN telecommunications network, the LRP-naïve trainee observed 6 LRP performed by a trainer located 200 km away from Hamilton to London Ontario (group1) (Figure 1). Using the same network, the trainee performed 6 LRP under the supervision of the remote trainer (group 2). The next six LRP procedures were performed by the trainee independently (group 3). The trainer and trainee were able to communicate back and forth using audio equipment and visual demonstration of anatomy and techniques were communicated via a pen and tablet video screen. The audiovisual feeds were facilitated by simple Polycom technology and ISDN lines. Due to weather issues, telecommunications failed in 1 case. Audiovisual communication was excellent and although visual delays were experienced, this did not greatly impact upon the success of the cases. The median operative times for the three groups were 200 min, 285 min vs. 250 min respectively (p = NS between groups 2 and 3). Median blood loss was not different between groups and no blood transfusions were performed. No anastomotic leaks, open conversion or intraoperative complications occurred. Of the patients with confined disease (pT2), only one patient had a local positive surgical margin (group 2) with all patients having undetectable disease at 1 year. At the 1 year follow-up mark, 11/12 patients in group 2 and 3 have achieved complete urinary continence. Of 8 patients in the groups 2 and 3 that underwent bilateral nerve sparing, 38% of patients achieved potency by 12 months. It was concluded that telementoring could be performed to teach complex operative procedures such as LRP to surgeons. Similarly, Schlacta's group from our centre had successfully trained less-experienced community-based general surgeons (through direct local and telementoring) to perform laparoscopic colon surgery. Although 33% of cases were converted to standard open procedures, the group concluded that there was excellent incorporation of laparoscopic colon surgery into this community-based practice [9].

We conclude that performance of telementoring is feasible and that it is possible to teach complex operations with current technology. We also believe that telementoring does not need to be limited to MIS procedures. Although the majority of hospital administrators are facile with teleconferencing, and telemedicine has been explored by a number of physician groups for patient care and education, surgeons have been slow to adapt to the same technology. We have shown that telementoring using ISDN lines is feasible and relatively inexpensive, utilizing existing communication lines. However, its eventual adaptation in healthcare will depend on further education and an evolution in surgical thinking.

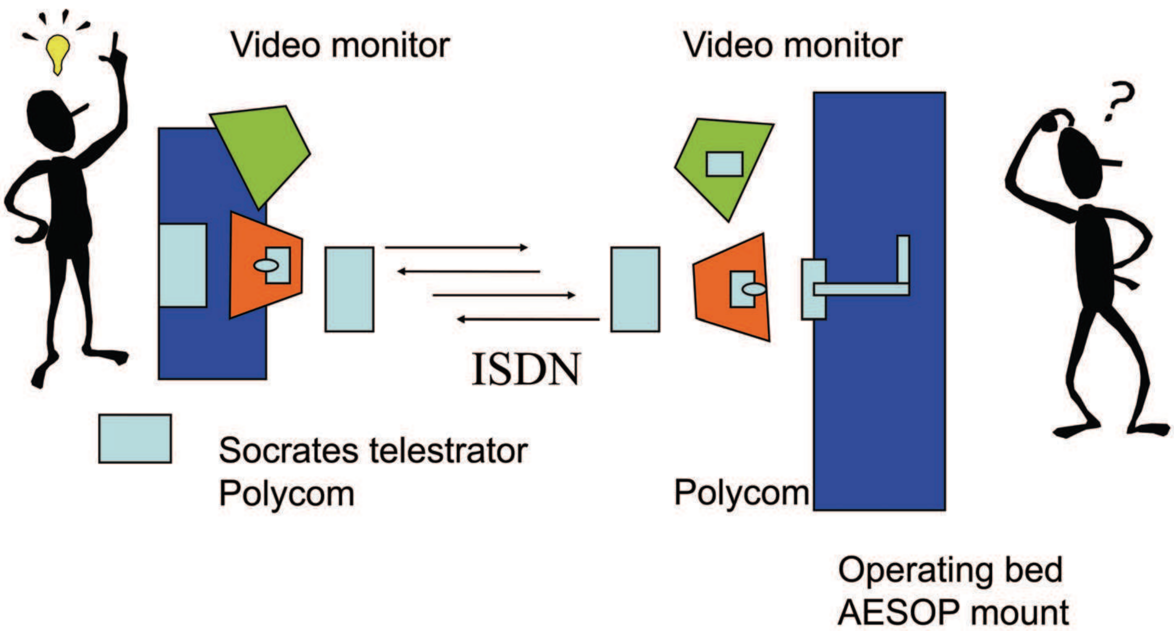

Fig. 1. Telementoring set-up. The set up in our telementoring procedures involved 4 ISDN lines as well as audiovisual Polycoms, and video screen telestrator. The AESOP laparoscope holding robot was used during early, but not later clinical use. The mentor is pictured on the left while the trainee along-side the OR table is pictured on the right hand side.

4. Telesurgery

Telesurgery involves a surgical procedure with the surgeon being situated remotely from the patient. The history of telesurgery dates back to the first commercial application in laparoscopy. The Automated Endoscopic System for Optimal Positioning (AESOP™) was FDA approved in the United States in 1993 and was used solely to guide the laparoscope. When it was initially introduced, the surgeon controlled the robotic arm either manually or remotely with hand or foot switches. Later versions were modified and equipped with voice controls. Although the use of has been associated with 'telementoring procedures', its development gave way to the complex three armed robotic technology that integrated instrument manipulating arms as well.

The manufacturer of the AESOP™, Computer Motion Inc., would later introduce the three armed ZEUS™ robotic system onto the U.S. market in 1998. Concurrently, Intuitive Surgical (Sunnyvale, California) released yet another 3-arm surgical robot, the da Vinci®. Developed from technology designed by NASA, the da Vinci® was originally intended for use by the U.S military, but was quickly adopted for civilian use. In 2003, a merger between Computer Motion Inc. and Intuitive surgical paved the way for the da Vinci® robot, along with it's newly FDA approved EndoWrist™ technology, to dominate the surgical robot market worldwide. The large majority of published literature on robotic-assisted surgery to date, has employed the use of the da Vinci® system. Currently, it is the only commercially available surgical robotic system.

The da Vinci® consists of separate components. The surgeon sits at the console where he/she is able to visualize the surgical field in 3D and operate several hand and foot controls. The surgeon's motions are processed by a computer system and relayed to the robotic arms. The robot has three arms. The central arm holds the camera and 2-3 outer arms hold the surgical instruments, which articulate at the EndoWrist™. This allows the instruments to move with seven degrees of freedom and two degrees of axial rotation, eliminating many of the difficulties associated with standard laparoscopic procedures.

Initially, commercial surgical robots were intended to perform minimally invasive cardiac procedures. However, since the initial description for robot assisted closed-chest coronary artery bypass grafting at our centre in 1999 [10], applications for robotic surgery have been rapidly growing. Since its inception, robotic surgery has not only expanded to other cardiac surgical procedures such as left internal mammary artery take-down and mitral valve repair, but also several gastrointestinal, gynecological and urological procedures. These included: cholecystectomy, Nissen fundoplication, Heller myotomy, pancreatectomy, hepaticojejunostomy, gastric banding, distal gastrectomy, Roux-en-Y gastric bypass, colectomy, tubal re-anastamosis, hysterectomy, nephrectomy, pyeloplasty, adrenalectomy, aneurysm repair and radical prostatectomy, among others. Due to the increased precision and dexterity that the robot contributes to the case, the robot has been exploited for radical prostatectomy more than any other procedure, since it has allowed laparoscopically naïve surgeons to perform laparoscopic suturing to perform critical anastomotic maneuvers with relative ease. We have shown that the robot improves the performance of experienced laparoscopic surgeons as well [11].

Of relevance to telesurgery, these robotic platforms were designed using connections that permitted surgery to be performed with the surgeon at a console remote from the bedside robot and patient. In fact, the original intent was to permit the surgeon to perform surgery just as easily in another room, another building, another continent, or in outer space. Indeed, any surgical procedure with the surgeon sitting remotely from the patient could be considered remote telesurgery. However, it is the possibility of performing long-distance telesurgery that stirs the imagination.

Most notably, in 2001, Marescaux et al. revolutionized surgery by performing a trans-Atlantic robotic assisted cholecystectomy using the ZEUS™ robot [12]. The surgeon and console were located in New York, and the patient and effector arms were in Strausbourg, France. Asynchronous transfer mode (ATM) technology was used to establish connections via high-speed terrestrial fiberoptic networks with a bandwidth of 10Mb/s. These connections were reserved exclusively for the procedure that ran a round-trip distance of 14000 km. Although there was a lag time of 155 ms, the laparoscopic cholecystectomy was completed without incident over 54 minutes. It should be noted that although audiovisual interactions and robotic arm movements were performed through the trans-Atlantic connections, the application of 'electrocautery' to dissect the gall bladder, placement of clips, introduction of the ports, and closure of port-sites had to be performed by the bed-side assistants. As well, laparoscopic cholecystectomy is a relatively simple laparoscopic procedure and could have been easily completed by the bed side surgeons with greater ease and in less time. Although the cost of this solitary operation was astronomical, it demonstrated that 'real world' long-distance telesurgery was feasible, and if the lag time could be limited to <155 ms, surgeons could perform simple procedures from their home base, even if the patient was on a battlefield or in the far reaches of space.

The next natural step in the evolution of telerobotics was to employ this technology to help train and certify surgeons in 'real world' distant or remote communities. This would allow an expertly trained surgeon at a central location to provide assistance and collaboration during a new or challenging procedure to a less experienced surgeon in the community. This would also provide community surgeons in remote areas a means to gain advanced laparoscopic skills, as well as provide patients access to tertiary care level surgical procedures without having to travel.

Although this concept seems intuitive, reports of these practical applications are rare and the anticipated adoption of this technology into the current day clinical practice remains sporadic. Reasons for this may include: the amount of time and organization involved at both sites, financial burdens of the technology and equipment, and a lack of a dedicated and safe network with sufficient bandwidth to transmit such data.

Another group in Ontario, Canada has demonstrated their successful integration of telesurgery into clinical practice. Anvari et. al. [13] used telesurgery on a routine basis to both assist and mentor surgeries requiring advanced laparoscopic skills at a remote hospital over 300 miles away. Commencing in February 2003, one year after the trans-Atlantic cholecystectomy by Marescaux, Anvari was able to provide a "Telerobotic Surgical Service"; using telesurgery, he successfully completed 21 laparoscopic procedures over a two-year period. All surgeries were successful with no major intraoperative complications, including no open conversions. Surgical outcomes were equivalent to those of the same laparoscopic procedures performed at a tertiary center. The array of surgeries performed included: 13 fundoplications, 3 sigmoid resections, 2 right hemicolectomies, 1 anterior resection, and 2 inguinal hernia repairs. The amount of time spent by each surgeon performing the surgical dissection in each case was equally allocated between mentor and trainee. Furthermore, both surgeons were able to operate together using the same surgical footprint, swapping roles seamlessly throughout the procedure.

The group utilized a commercially available network (15 Mbps of bandwidth) to connect the two hospitals. An overall latency of 135-140 ms was incurred, but surgeons were able to compensate with this delay. The Zeus™ surgical system used in all cases, with the console in Hamilton and the operating arms at the operative bedside in North Bay, Ontario.

Overall, the work by Anvari demonstrated that routine telesurgery is feasible, although the full extent of its role as an adjunct to telementoring remains to be determined. As the cost of surgical systems decrease and reliable data networks become more available, barriers preventing the routine use of telesurgery may fall, allowing a more broad involvement in future surgical practice.

5. Limitations of telesurgery

Although successful clinical telerobotic surgery has been accomplished, most cases were simple and did not require extensive dissection, suturing and knot tying. Delays incurred through transmission of telesurgical data through the communication circuits and codecs result in slowing of surgeon movement to account for asynchrony in motor output and visual input. It was not clear whether there was a temporal delay (latency) incurred by distance that would preclude the ability of the surgeon to compensate for visual-motor asynchrony, leading to excessive errors and abandonment of relatively complex procedures.

Utilizing a Zeus™ robot and real-time, internet protocol virtual private network (IP-VPNe) as well as satellite links, 18 porcine pyeloplasty procedures were performed by our group. The pyeloplasty procedure was used as our operative model, since it requires fine operative suturing with requirements of knot tying to accomplish 'water tight' anastomotic competence. The IP-VPNe network consisted of two redundant 17 Mbps IP connections at the surgeon console and two redundant 17 Mbps connections at the operative subject side cart (in London, Ontario), providing highly available WAN access to the Bell Canada VPNe Core network within our test laboratory. The WAN connections were then looped back at the Bell Canada central office in Halifax Nova Scotia, which added 4150 km round trip distance between surgeon and surgical subject sides (both in London, Ontario) (Figure 2). The satellite network was privately partitioned with 10 Mbps bandwith. The routing was a round trip connection from London to Toronto, Ontario, to a telecommunications satellite (Telesat Canada) operating in the Ku band (12-14 GHz) and back to London Ontario, traversing a distance of 71,000 km [14].

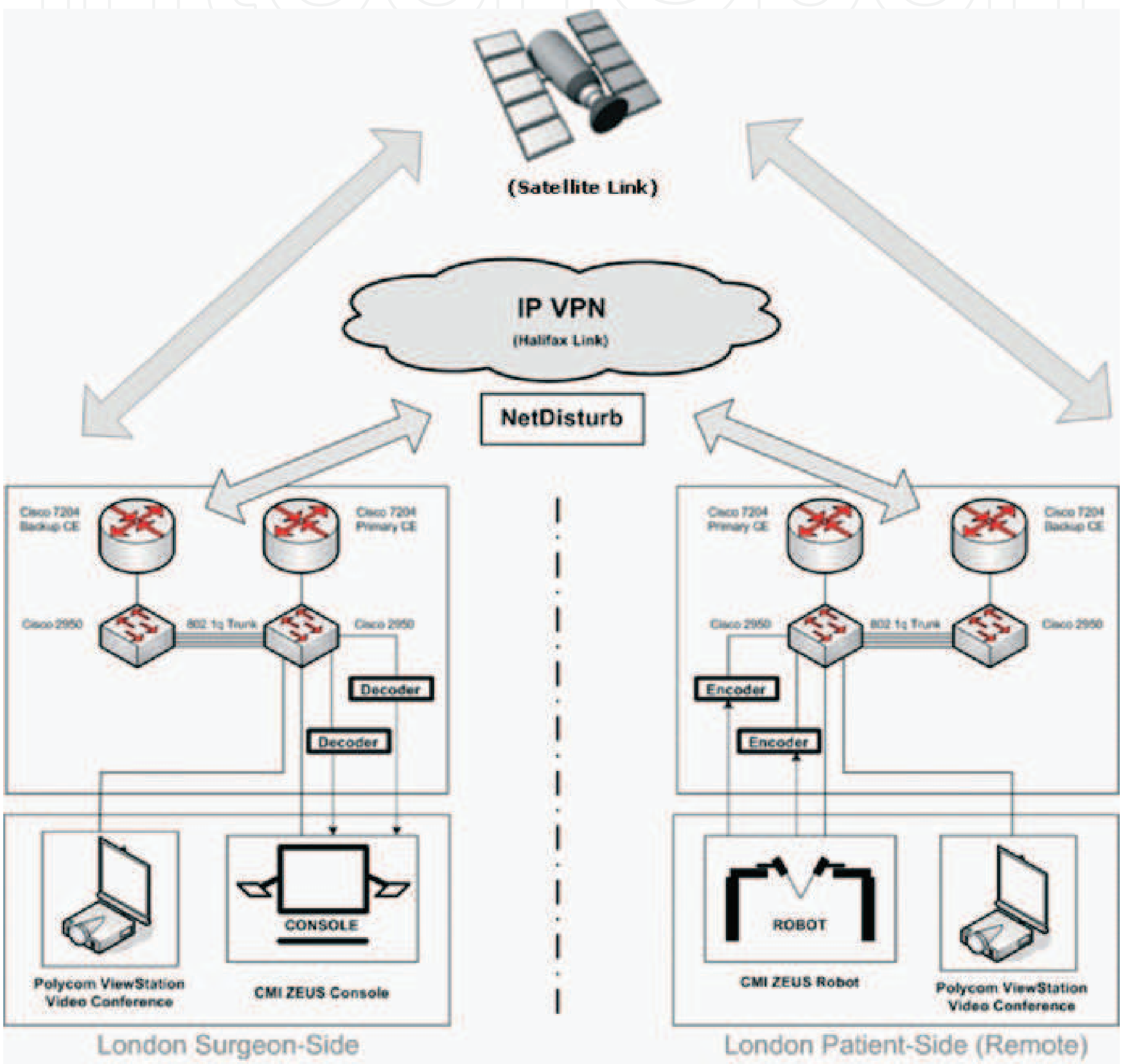

Fig. 2. Hardware set-up of the London-Halifax and satellite telesurgery loops. These loops were used to facilitate telesurgical experimental procedures. This permitted all experiments to be performed in one location, despite telesurgical routes over 4000 km long. Left hand side of figure outlines surgeon console and associated connections, right hand side illustrates telesurgical accessory surgeon console and patient side cart with associated connections.

Network latencies encountered during the trial were 66.3 +/- 1.5 ms for landline and 560.7 +/- 16.5 ms for satellite. During the procedures through landline, VPNe and satellite, fluid robotic motion and faithful visual rendering of the operative field was achieved. Network bandwidth was measured, requiring only 23 Mbps of budgeted 45 Mbps required during the procedures. Operative duration with real-time connection (41.3 +/- 15.0 min) was not significantly different vs. VPNe landline (47.0+/-24.1 min) vs. satellite (51.8+/-4.7 min). The anastomotic competence of the pyeloplasty procedures were excellent in all groups as well [14]. Although it was subjectively more challenging to perform pyeloplasty in the landline and satellite groups, it was shown that complex operative procedures requiring delicate suturing and knot tying could be accomplished using long-distance landline and satellite connections. The fact that operative times and errors were similar between groups indicate that surgeons experienced in telesurgery and robotics are capable in adapting to an operative environment in which latency and network jitter affect the human-machine interface.
Using the same 4150 km 'London to Halifax to London' loop, the ability to perform telesurgery in the same porcine pyeloplasty model was assessed 1 year later using the advanced da Vinci® robotic platform. A maximum of 23 Mbps of budgeted 45 Mbps were required for telesurgical operations, but 3-D stereoscopic vision was lost from the long-distance cases vs. the direct connection controls. Network latencies were similar at 66.1+/-1.5 ms. Network jitter ranged from 0-5 ms and no network failures occurred. With the da Vinci® procedures, operative times were significantly faster than with the Zeus™ procedures, but it was also apparent that with the use of more efficient robotic technology, the long-distance IP-VPNe operations took significantly more time vs. direct cable links (20.7+/-4.7 min vs 10.9+/-1.1 min, $p<0.01$). As well, there were no anastomotic discrepancies in any cases performed (total 12) [15]. We concluded that as robotic technology advanced, surgeries became more facile and the detriment of network latency and jitter were more apparent in our later trials. However, the impact of losing 3-D vision through the VPNe network as it related with operative time is not known.

6. The limits of bandwidth and latency

Our labs performed a series of experiments to quantify maximal tolerable latency during typical surgical maneuvers. Using randomized latencies, task times were significantly higher compared with zero delay at latency times of 500 ms and above ($p<0.01$; Figure 3) [16]. As noted earlier, the root cause of this delay are related with the encoding and decoding processes rather than the physical separation distance between operating sites. Already, we have seen significant progress in codec speed and capacity rates facilitating transmission of dual high definition signals.
Communities without broadband access may need to rely upon satellite communication to support telemedicine. In order to quantify telesurgery applications, our group performed porcine internal mammary artery (IMA) dissection using both IP and satellite networks described earlier [16-18]. There was no significant difference in the time to perform IMA dissection (p = NS). Using a multi-criteria Global Rating Scale, we found that there was also no significant difference in the quality of surgical performance. Bandwidth of the satellite feed was progressively pared down to identify a failure point for the video signal. Telesurgery was no longer possible at bandwidth of approximately 4 Mb/s or less, as determined by the operator and an experienced robotics observer team (Figure 4)[19].

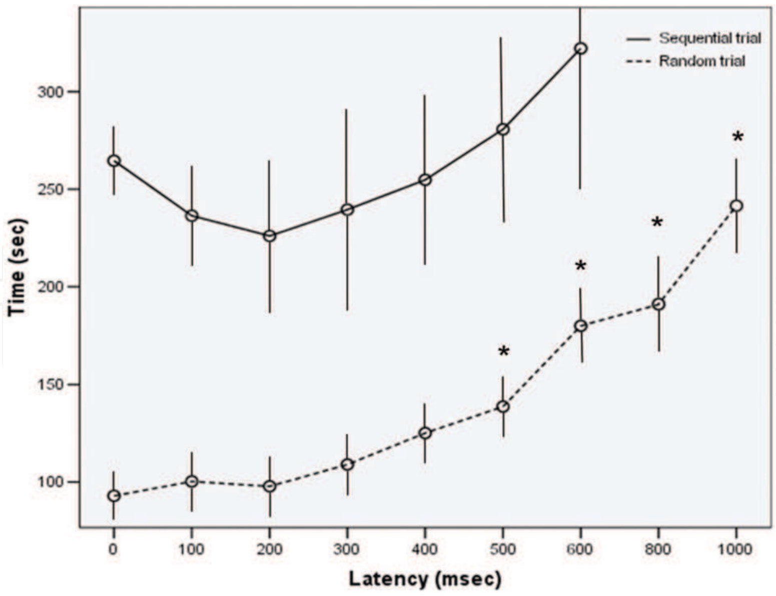

Fig. 3. Overall time for task completion of dry lab objects for sequential and random delay trials at differing latencies. Random trial times were significantly greater compared to zero latency at 500 ms and beyond (repeated measures ANOVA, * $p < 0.001$)

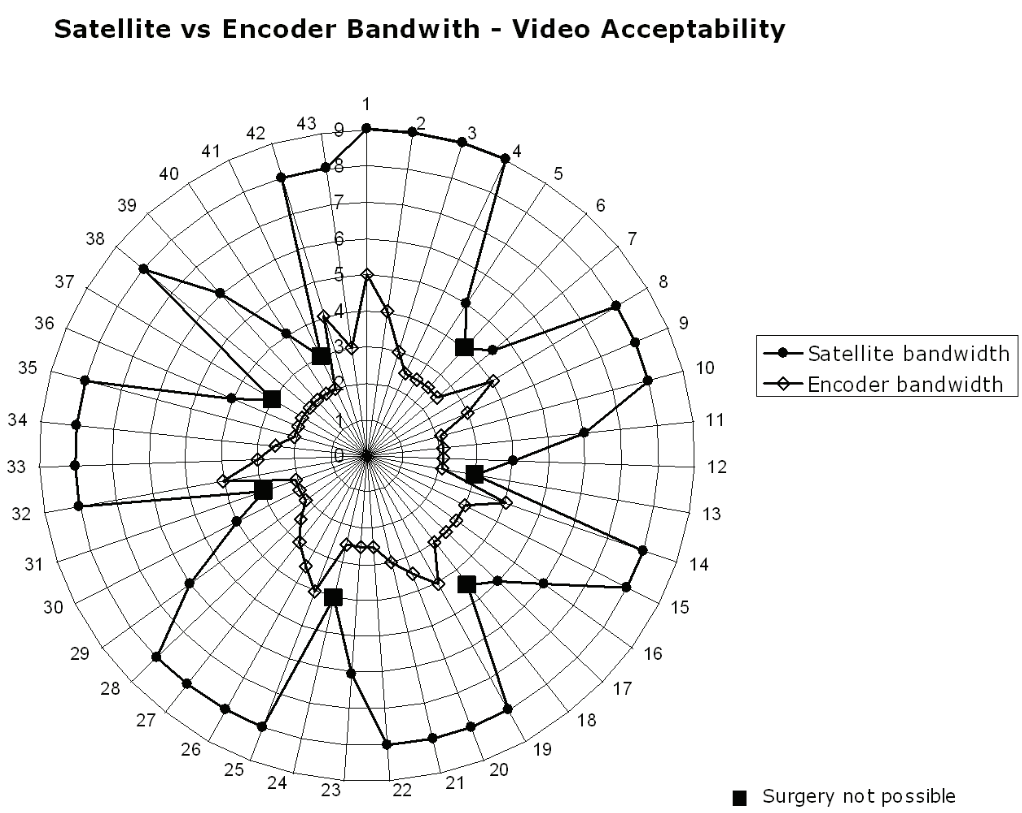

Fig. 4. Satellite and encoder bandwidths were sequentially decreased to identify a minimum level for telesurgery. The bandwidth 'pipe' is shown as concentric circles (9–0 Mb/s). Changes in bandwidth combinations using 7 pigs are seen radially in the 43 spokes. ■, satellite bandwidths at which surgery was no longer possible (approximately 4 Mb/s)

7. Pitfalls

Although the performance of complex operations from a distance has been shown to be feasible using existing technology, the provision of VPNe lines capable of supporting 48 Mbps was expensive ($30,000/ month). There are also issues regarding the medico-legal aspects of performing telesurgery. For example, who assumes the primary medico-legal responsibility for the long-distance procedure? Is it assigned to the bedside surgeon or the experienced surgeon based from afar? What happens if the telecommunication system fails? Are encrypted VPNe systems truly protected from individuals that are capable of 'hacking' into IP lines? There are other issues that exist for the telementor. How do we decide who is credentialed to be a mentor and how do we assign responsibility if the case goes awry? If the most experienced surgeon needs to assume responsibility, then it may be impossible to find any experts that would take on the responsibility of primary patient care without established and reliable financial or academic reward.

8. Future of telesurgery

Technologically, telesurgery will become more facile as network latency becomes reduced through the use of more efficient codecs and the advancement of surgical robotics. However, the development of telesurgery is contingent upon surgeon acceptance, need, and development of routine use, which would be associated with reduce costs. In fact, there may come a time that a surgeon performing robotic surgery may find a colleague to assist in a challenging operation through telesurgical operation of a fourth robotic arm. It would be as simple as dialing up a senior colleague to facilitate the operative procedure. Using telesurgery, that senior colleague may be dialed into an operation that is taking place a thousand miles away.

9. Conclusion

In conclusion, telementoring has been shown to be feasible, inexpensive and an effective tool to facilitate the development of surgical training in remote locations. Currently, its major limitations reside within limited access to trainers, perceived need, and the slow trickle of technology into the operating room. Long distance telesurgery, despite network latency and jitter, has been shown to be feasible, effective but very expensive. It requires significant amount of resources, including a robot in the remote centre, and bedside assistants that are capable of providing a fallback plan in case of technical failure. Ongoing clinical needs and evolving robotic and telecommunication technology are currently being evaluated.

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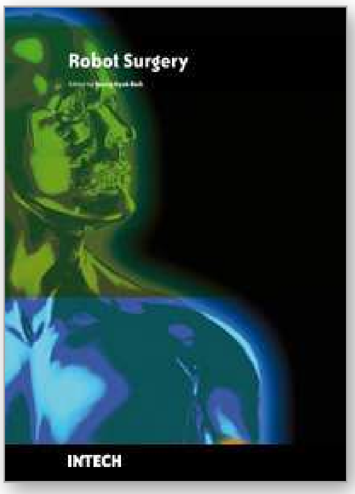

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Robotic surgery is still in the early stages even though robotic assisted surgery is increasing continuously. Thus, exact and careful understanding of robotic surgery is necessary because chaos and confusion exist in the early phase of anything. Especially, the confusion may be increased because the robotic equipment, which is used in surgery, is different from the robotic equipment used in the automobile factory. The robots in the automobile factory just follow a program. However, the robot in surgery has to follow the surgeon's hand motions. I am convinced that this In-Tech Robotic Surgery book will play an essential role in giving some solutions to the chaos and confusion of robotic surgery. The In-Tech Surgery book contains 11 chapters and consists of two main sections. The first section explains general concepts and technological aspects of robotic surgery. The second section explains the details of surgery using a robot for each organ system. I hope that all surgeons who are interested in robotic surgery will find the proper knowledge in this book. Moreover, I hope the book will perform as a basic role to create future prospectives. Unfortunately, this book could not cover all areas of robotic assisted surgery such as robotic assisted gastrectomy and pancreaticoduodenectomy. I expect that future editions will cover many more areas of robotic assisted surgery and it can be facilitated by dedicated readers. Finally, I appreciate all authors who sacrificed their time and effort to write this book. I must thank my wife NaYoung for her support and also acknowledge MiSun Park's efforts in helping to complete the book.