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Telemedicine in Surgery: What are the Opportunities and Hurdles to Realising the Potential?

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Abstract Since the first telegraphic transmission of an electrocardiogram in 1906, technological developments have allowed telemedicine to flourish. It has become a multi-billion pound industry encompassing many areas of medical practice and education. Telemedicine is now widely used in surgery from performing operations to teaching and can be divided into three main components; telesurgery, telementoring and teleconsultation. Developments across these fields have led to remarkable achievements such as intercontinental telesurgery and telementoring. However, barriers to the further implementation of telemedicine remain. In this review, the developments and recent advances of telemedicine across the three domains are discussed together with the challenges and limitations that need to be overcome.

Keywords Telemedicine · Telesurgery · Telementoring · Teleconsultation · Urology · Surgery

Introduction

The integration and application of communications technologies in medicine has a long history from the first use of the telegraph to transmit an electrocardiogram in 1906 [1]. As new technologies have been developed, their incorporation into medicine has continued to flourish. Following on from the initial experiments with the telegraph, each new wave of communications technologies has inspired assimilation into medicine. The Australian Royal Flying Doctor Service were early pioneers of telemedicine, developing innovative solutions to delivering medical care across vast distances. From their foundation in 1928, they used a pedal wireless to conduct teleconsultations initially in Morse code then voice radio [2]. In 1950, Gershon used a fax to send X-rays, and Debakey pioneered the first educational teleconference in 1962 presenting an aortic valve replacement [3, 4]. Telemedicine is now a multi-billion pound industry that plays important roles in medical practice and education. It can be divided into three main components: telesurgery, telementoring and teleconsultation.

Telesurgery

Telesurgery is defined as remote operating through the use of a surgical robot actively controlled by a distant operator. Telesurgery has only been made possible by the advent of robotic-assisted surgery.

The concept arrived in the operating room in 1985 with the PUMA 200 robot for CT-guided brain biopsy. This was followed swiftly by the PROBOT in 1988, an ultrasound-guided independent robotic system for prostatic resection [5, 6]. The major development of telesurgery came with the introduction of master-slave surgical robots such as the ZEUS system ® (Computer Motion, Goleta, CA) and, more recently, the da Vinci ® Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA). Such a system was used in the landmark study of the first transcontinental telesurgical operation in 2001, Operation Lindbergh. Professor Marescaux performed a laparoscopic cholecystectomy on a 68-year-old lady in Strasbourg, France, using a ZEUS robotic system positioned

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in New York, USA [7]. The procedure was performed without complication, and the patient was discharged successfully 48 h later.

Since then, there have been a number of further trials of various procedures. To date, the only telesurgical randomised controlled trial involved percutaneous access to the kidney with a remote center of motion robotic device (PAKY-RCM) (see Fig. 1). Comparing human and robotic percutaneous renal access, this landmark study demonstrated the feasibility of transatlantic telesurgery with the robot working equally efficiently when controlled at a distance of 5 m or 5000 miles [8]. More advanced surgical robots have allowed more complex cases to be performed and has even led to the introduction of a routine telesurgery service in Canada [9]. Operations have ranged from laparoscopic Nissen's fundoplication to laparoscopic hemicolectomies, anterior resections and sigmoid resections. A commercially available IP/VPN (Internet Protocol-Virtual Private Network) was used to link the two hospitals. This allowed skilled laparoscopic surgeons to control a Zeus TS "microjoint" system robot 400 km away. A highest priority quality of service ensured that the teams' data connection took priority over all other traffic on the network. This resulted in an overall latency (time delay) of 135–140 ms, which although noticeable, was short enough for the surgeons to adapt to it. There were no major complications, and in the subsequent cases, the telerobotic surgeon was also able to mentor the local resident surgeon. Only one technical disturbance forced a switch to the secondary telecommunication line without any deleterious effect on the patient or operation. This study helped to demonstrate the feasibility of routine telerobotic surgery using a commercial fibre optic cable rather than the asynchronous transfer mode band used by Professor Marescaux.

One of the major problems that must be overcome in telesurgery are the delays in sending and receiving the audio-visual feed, known as the latency time. During Marescaux's pioneering laparoscopic cholecystectomy, close attention was paid to the data connection. A high-speed fibre optic cable with a dedicated asynchronous transfer mode (ATM) connection was used. Additionally, a 10-mb/s bandwidth was reserved for the sole use of the procedure, and the quality of data transfer was measured throughout the operation. As a result, an average latency of 155 ms was achieved only minimally impacting on the surgeons' performance. Yet, this required the involvement of 40 technicians and support personnel. Without the benefit of such high-speed data connections, longer latency times can have significant and adverse effects on a surgeon's ability to operate. A number of studies have investigated the effect of increasing latency time on surgical performance. They have shown that there is an exponential reduction in surgical performance as latency times increase. A latency of less than 300 ms has been found to be generally acceptable to surgeons, with a minimal effect on the surgery [10•, 11]. At the other end of the spectrum, lag times of over 700–800 ms lead to significant and unacceptable reductions in surgical performance. Practising operating with a time delay

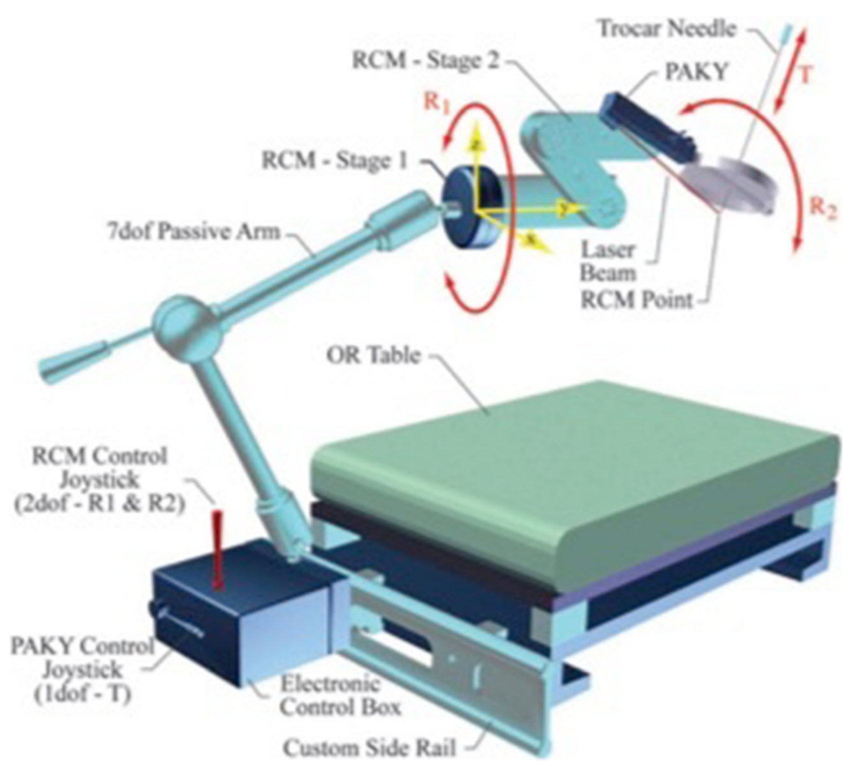

Fig. 1 Percutaneous access of the kidney (PAKY) device with remote centre of motion active robotic device (RCM)

using stimulation training has been to improve performance. However, the training effect was small and limited to simple tasks [12]. Longer latencies also increase strain on surgeons and operative time. Therefore, whilst various studies have shown that surgical exercises can be performed competently with longer latencies (500–600 ms), the resultant increase in strain and procedure time may have a significant clinical impact [13, 14]. Whilst task complexity and a surgeon's competency also affect the ability to compensate, lag times of less than 300 ms are now generally accepted as necessary for surgery to be performed safely.

Despite the technical limitations, surgical teams across the world have been working to increase the scope of telesurgery. The expansion of telesurgery to remote and hostile environments is an area in which there is great potential for development. There are substantial advantages in being able to offer patients surgical treatment within their communities, not only to the patient but also to the health system in general. Patients will be spared lengthy travel for perioperative care whilst still being offered optimal surgical care from specialist centres [15].

The possibility of being able to perform surgery locally has always been very attractive in the military trauma setting. Yet, whilst the benefits of telepresence surgery for treating military casualties has been widely discussed, e.g. the trauma pod [16], no systems have yet been introduced. To date, the main benefits of telemedicine for the military have been to provide expert input in specialities ranging from dermatology to orthopaedics across the areas of deployment [17, 18].

Stretching the boundaries even further, the NASA Extreme Environment Mission Operations (NEEMO) have conducted several experiments assessing the feasibility of operating in extreme environments such as space. A number of experiments were conducted performing telesurgical procedures such as repair of a vascular injury, laparoscopic cholecystectomy and abdominal surgery on models [19]. Surgical operators were based 2500 km away using the commercially available AESOP robot as well as two prototypes, NASA's M7 and RAVEN robots. In addition to this, zero-gravity robotic experiments were also conducted in 2007 using the M7 robot to perform suture tasks [20]. A major challenge operating in any extreme or remote environment is a limited communication infrastructure. Whilst commercial services in developed nations may be able to offer low latencies, in remote areas, transmission speeds are likely to be substantially slower if available at all. Satellite networks offer an alternative; however, currently longer latency times and restricted bandwidth limit their use in telesurgery [21].

Telementoring

Despite laparoscopic surgery being widely embraced, training in advanced minimally invasive techniques remains a significant issue especially in smaller, more remote hospitals. Often, the only training options available are hands-on-courses, surgical fellowships and mentoring programmes either in house or involving site visits [22]. Hands-on-training and mentoring remain the most effective tools for learning. However, their utility is limited both by the costs and the need for skilled mentors. Expert surgeons rarely have the time or availability to take part regularly in such programmes, given the burden of travel and time away from their own institutions. A solution is telementoring, consisting of remote guidance and assistance using telecommunications technologies. Alongside telesurgery, telementoring represents an advanced application of telemedicine. It encompasses a wide range of activities, whereby a health professional can guide and teach remotely. A key aspect is the two-way exchange of information in real time between the mentor and trainee. It can range from simple voice commands whilst real time video is watched to more complex tasks such as assisting the mentee in surgery or using on-screen demonstration using cursors or line indicators (telestration) (see Fig. 2).

Telementoring was first performed by Moore in 1996 using the AESOP system to telementor 23 urological operations, 22 successfully [23]. Subsequently, Camara et al. used conventional ISDN lines to mentor an endoscopic dacryocystorhinostomy with live question and answers transmitted between Honolulu, Hawaii, and Manila, Philippines [24]. Extending this further, Lee et al. were able to use a computer-based system and public telephone lines to telementor laparoscopic varicocelectomy, adrenalectomy and nephrectomy [25]. With the feasibility of telementoring established by these and other studies, a more extensive trial was conducted between the USS Abraham Lincoln Aircraft carrier battle group cruising the Pacific Ocean and various locations in the USA. Using satellite communication systems, surgeons in California and Maryland were able to mentor on-board surgeons in various laparoscopic procedures. A delay of

Fig. 2 Mr. Justin Collins telementoring a robotic prostatectomy

up to 12 s in video transfer needed to be circumvented with transfer of supplemental voice and still picture instructions. This allowed all five laparoscopic hernias to be successfully telementored [26].

Like telesurgery, telementoring relies on a real-time audio and visual interface. This requires high-speed data connections. Developments in connection speeds have played a major role in allowing the expansion and development of telementoring. In initial studies, conventional telephones with digital-to-analogue modems gave transfer speeds of up to 21.6 kbps. Resultant time delays of up to 12 s rendered anything beyond basic telementoring impossible. With the introduction of 128-kbps ISDN and even faster ASDL lines, time delays have fallen to less than 150 ms allowing more complex and interactive mentoring systems.

Since then, there has been a large expansion in telemedicine both geographically across the globe as well as across surgical specialities. Significant developments have included expansion into developing countries. Rosser et al.'s "Operation Messiah" used a portable satellite-based connection to mentor a surgeon in the Dominican Republic in various laparoscopic procedures [27]. Subsequently, Rosser was able to develop this further. Using a mobile surgical unit in combination and a low mobile low-bandwidth data connection, the team in Yale was able to mentor a laparoscopic cholecystectomy in rural Ecuador [28].

Even technically challenging procedures such as hand-assisted laparoscopic donor nephrectomy have been successfully telementored. A team in London, UK, was telementored by surgeons based in Minnesota, USA, allowing them to initiate an independent local practice [29].

However, whilst there is now a large body of literature detailing numerous pilot studies and case series in telementoring, definitive assessment of its effectiveness with larger, objective trials is lacking. A meta-analysis of telementoring only identified three randomised trials. Interestingly, whilst the results appeared to show low complication rates, 5% across 433 procedures, and high trainee satisfaction, every trial demonstrated surgical improvement [30].

Given the high cost of specialised communication hardware and software, there has been a considerable expansion in the adoption and experimentation with off-the-shelf technologies. Various solutions have been tested in the literature; for example, using video clips recorded on a blackberry to provide remote assistance for junior surgeons performing laparoscopic cholecystectomies [31]. This trial did demonstrate the potential feasibility of using mobile phones to view surgical video clips, but the lack of real-time two-way communication limits its applicability. In the last year, there have been a number of new trials to develop the technological protocols for telementoring. Other examples of the use of off-the-shelf technology have been the incorporation of Google Glass (Google, Mountain View, CA, USA) into telementoring programmes. Studies have found it effective in a variety of settings ranging from teaching cardiac ultrasound to medical students [32] to mentoring percutaneous closure of a patent foramen ovale [33] and in limb salvage surgery [34].

At the opposite end of the spectrum, specialist telementoring systems such as the Connect™ system from Intuitive System (Intuitive Surgical, Sunnyvale, CA, USA) [35•] have been developed. This purpose designed, second generation telementoring system fully integrates with the da Vinci robotic surgical system (Intuitive Surgical, Sunnyvale, CA, USA). It allows distant mentoring with one-way video, two-way audio and telestration using either wired or wireless connections across standard network connections. Within the confines of closely selected trainees and cases, the authors found that the system could be effective in mentoring trainees through parts of robotic-assisted nephrectomies and prostatectomies. Both wireless and wired connections provided lag times of less than 14 ms, and differences between the two were not noticeable. However, of the 27 remote mentoring cases, one had to be abandoned due to "video freeze" and was then removed from analysis. A Japanese team has developed a similar system. The telestrating and telementoring applications allowed the mentoring of 120 radical prostatectomies. As in the majority of previous studies, telementoring was found to be just as effective as in-room instruction [36•].

Teleconsultation

Aside from the benefits that telemedicine brings to surgical education and training, it also offers promising solutions to healthcare disparity especially in rural and isolated areas. Unlike telesurgical and telementoring applications, teleconsultation is now widely available through low-cost web and telephone-based consultation software. These allow real-time audiovisual interaction with minimal requirements for technical support. The recent emergence of ever more powerful and affordable off-the-shelf devices has further facilitated this expansion. Yet, there has also been an increase of "low-tech" teleconsultation solutions. For example, a long-standing email-based vascular service open to the general public has been run for 13 years [37].

One of the most iconic developments has been "telerounding" or remote patient rounding. Using video conferencing facilities, the lead surgeon (or physician) interacts with his patient remotely, maintaining regular doctor-patient interaction and ensuring continuity of care. It was first introduced by Ellison et al. in 2004 using a computer and camera installed on remotely controlled robotic platform. [38] A specially designed robot or "roboconsultant", the RemotePresence-7 robot (InTouch Health, Santa Barbara, California), has now also been developed. It allows an individual to project himself to a distant location, using the robot

Table 1 Major milestones in the development of telemedicine

Date	Team	Procedure	System used	Success rate	Communication system	Comments
1906	Einthoven [1]	Trans-telephonic transmission of the ECG		1/1	Telegram	
1950	Gershon [3]	Fax transmission of X-Ray			Facsimile	
1962	Debakey [4]	Video conference demonstration of aortic valve replacement		1/1	"Early Bird" satellite	Live Q&A between the USA and Switzerland
1996	Kavoussi [23]	Telementoring of pelvic lymphadenectomy, diagnostic laparoscopy, renal biopsy, radical and partial nephrectomy, pyeloplasty, bladder neck suspension, orchiopexy, ureterolysis	AESOP	22/23	Fibre optic connection	Procedures mentored locally (sites 1000 ft apart); single failure due to robot malposition
1998	Rodriguez [24]	Telementoring of endoscopic dacryocystorhinostomy		1/1	ISDN; 128 kb/s connection; 500 ms latency	Intraoperative video conferencing with live Q&A between Hawaii and Philippines
1998	Kavoussi [25]	Telementoring of laparoscopic varicocelectomy, nephrectomy adrenalectomy	AESOP	3/3	3 ISDN lines; 384 kb/s connection; <1 s latency	Between the USA and Thailand (2 cases) and Austria
1999	Mendoza-Sagaon [26]	Telementoring of laparoscopic inguinal hernia repair	Battlegroup Telemedicine System (video and audio transmission)	5/5	Satellite link; 21 kb/s connection; 2–12 s latency for video	Between the USA and Pacific fleet
2000	Savalgi [27]	Telementoring of Nissen's fundoplications, cholecystectomy, and liver cyst excision		4/4	INMARSAT satellite link; 128 mb/s connection	Between the USA and Dominican Republic
2001	Marescaux [7]	Transatlantic telesurgical cholecystectomy	ZEUS	1/1	ATM; 10 mb/s connection; latency 155 ms	Between the USA and France
2004	Kavoussi [38]	Telerounding of postoperative surgical patients	InTouch Health Robot	27/27		Telerounding led to improvements in post op care and satisfaction
2004–2007	NEEMO missions [19]	Telesurgery in underwent environment (repair of vascular injury, laparoscopic cholecystectomy, simulated abdominal surgery)	AESOP; M7 Robot; RAVEN Robot		Microwave satellite connection; latency between 70 ms and 3 s	Between Aquarius, underwater habitat, surgeons and mainland USA
2005	Dasgupta [8]	Telesurgical access to the kidney	PAKY-RCM	152/152 insertions into kidney model	ISDN; 512 kb/s connection; latency 300 ms	Between the USA and UK; RCT comparing human and robotic performance
2005	Stein [9]	Telesurgical laparoscopic fundoplication, sigmoid resection, hemicolectomy, anterior resection, inguinal hernia repair	ZEUS	21/21	IP/VPN; 15 mb/s connection; 140 ms latency	Established routine telesurgical service in Canada
2005	Mamode [29]	Telementoring of laparoscopic hand-assisted donor nephrectomy		4/4	4 ISDN lines; 512 mb/s bandwidth; <500 ms latency	Between the USA and UK; independent practice implement following telementoring

Table 1 (continued)

Date	Team	Procedure	System used	Success rate	Communication system	Comments
2010	Patton [31]	Telementoring of laparoscopic cholecystectomies	Blackberry 8830 World Edition	10/10	Mobile internet connection	Between various locations; transmission of video clips
2014	Dawson [32]	Telementoring of echocardiography	Google Glass	6/6	Mobile internet connection	
2014	Uretsky [33]	Telementoring of percutaneous closure of PFO	Google Glass	1/1	Mobile internet connection	Remote assistance from expert cardiologist
2014	Hung [35•]	Telementoring of robotic radical prostatectomy and partial nephrectomy	Da Vinci surgical system with Connect™ software	25/26	Wired and wireless internet connection; 13 ms latency with wireless	Local telementoring (350 m distance); video freeze forced abortion of 1 case
2014	Fujisawa [36•]	Telementoring of robotic radical prostatectomy	Da Vinci robotic with purpose built telementoring system	60/60	Fibre optic connection; 1 gb/s connection; 255 ms latency	Local telementoring; no difference to in-room monitoring found
2014	Hurtt [42]	Teleconsultation follow-up of paediatric surgical patients	Commercial HD videoconferencing equipment	10/10	Wired internet connection	No postoperative complications

to see, hear, talk, move and interact in real time. Telerounding is now widely used in various specialities including challenging environments such as critical care. Not only does it provide a practical and flexible solution to the growing pressure on doctors to manage ever more diverse working pattern, but it has also been shown to increase patient satisfaction [39]. Trials have demonstrated that it leads to increased examination thoroughness [40]. Furthermore Several studies have also shown that, somewhat surprisingly, patients are happier interacting with their doctors remotely rather than being seen by other doctors. Technological developments in mobile computer technology have allowed telerounding to be performed using handheld devices such as tablet computers simplifying and reducing the costs of such systems [41•].

As a result, teleconsultation has undergone widespread expansion. As mentioned above, one of the main areas in which teleconsultation in surgery has been highly effective is the provision of pre- and postoperative care especially to rural or isolated patients. Canon et al. demonstrated its feasibility even in a paediatric population following urological surgery [42]. Particularly in subspecialist areas, patients often have to travel long distances to see the surgical teams imposing a significant burden. Through their teleservice, Canon et al. were able to save families an average of $88 and 2.6 h per consultation [42]. Like the email systems, other more low-technique systems have also been developed such as a mobile "app" which took over from a telephone-based follow-up service for ambulatory plastic surgery patients [43]. This allowed patients to regularly submit multiple questionnaires and surgical-site photographs. The system proved to be cost-effective for both the health service and patient-incurred costs (e.g. travel costs, time lost).

Surgery in remote locations has also benefitted from telemedicine. Not only does it offer greater provision for distance supervision and mentoring as described above but also in the perioperative period. Surgeons from Southern Illinois used store and forwarding software to aid preoperative planning [44]. Hereby, patients' details and pictures were uploaded and transmitted across the internet allowing surgeons to make more accurate decisions on surgery and suitability of patients. Using a low-cost internet-based system greatly improved the efficiency of screening and preparing patients for surgery then carried out by the American surgeons.

Challenges and Limitations

It is clear to see from the cornucopia of various technologies and systems employed that telemedicine has a vast amount to offer surgery. However, there are a number of barriers to translating these, often experimental, technologies into sustainable, effective components of modern medicine.

The legal implications of telemedicine especially cross-border applications remain ambiguous. In this regard, the health industry lags far behind other international industries such as banking. Issues such as malpractice and liability are, arguably, even more important in telemedicine when the usual face to face engagement with patients is lost. [45•] The EU does not make any specific provisions for doctors who practice telemedicine, and although individual countries usually have their own official body to oversee medical practice and can take disciplinary action on doctors on their medical registers, they do not have any jurisdiction over doctors registered abroad. Likewise, clinical governance is an important but largely untested issue. Assessing the quality of medical care delivered across borders can be challenging. Sharing and accessing medical records and images also poses questions for consent as well as data storage and confidentiality. Data confidentiality was the greatest worry in a survey on the prospects for telemedicine [46]. Secure data transfer and storage systems are essential for implementation; however, this comes at a price, which can limit its applicability.

Despite the expansion of low-cost technologies, cost can still be a problem especially in telesurgery when high-speed data connections and high quality audiovisual systems are required. Cost effectiveness is a growing concern for healthcare systems across the world, and therefore, the successful implementation of telemedicine requires cheap solutions. An aspect of this is the successful billing of services rendered. This can be especially problematic in inter-country or inter-state activities.

The Future

The expansion of telemedicine is certain to continue, and its applicability will only grow with the continued expansion of wireless, high-speed communication. High-speed networks are commonplace in the developed world, but the same does not apply to developing countries. Wider use of wireless networks is likely to accelerate this process and have already been shown to be technically feasible [47]. Applications within surgery are also likely to expand. Alternative devices such as tablet computers or Google Glass will play an increasingly important role in allowing doctors to work beyond their traditional geographic confines. Telesurgery and telementoring will also continue to expand to allow healthcare to become truly globalised (Table 1).

Compliance with Ethics Guidelines

Conflict of Interest The authors declare that they have no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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