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Man Li (Elina) Jin
Henry Ford Health, mjin2@hfhs.org

Meghan M. Brown

Dhir Patwa

Aravindh Nirmalan

Paul A. Edwards
Henry Ford Health, pedward2@hfhs.org

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Telemedicine, telementoring, and telesurgery for surgical practices

Man Li Jin, MD[a,*], Meghan M. Brown, BS[b], Dhir Patwa, BS[c], Aravindh Nirmalan, BS[d], Paul A. Edwards, MD[e]

Introduction

As advancements in technology and telecommunications provide us with infinite ways to close the distance between people, it has also led to the development of telemedicine and technologies to give greater health care access to patients in remote areas. Similarly, telesurgery has offered surgeons opportunities to collaborate and mentor trainees without restrictions of geography. Sophisticated technologies such as virtual reality learning systems, augmented reality technology, and haptic feedback have also emerged as promising methods of surgical training that are becoming increasingly more common in surgical training.

In this review, we explore the topic of telesurgery, telementoring, and telemedicine, and discuss the recent advancements of engineering and technology in this fast-growing field.

Telesurgery

Telesurgery describes a system in which the surgeon performs a surgery from a remote location separate from the patient. This difference of location may be cross country or even crossing continents. The surgery may be entirely performed by the remote surgeon through a surgery robot on the patient's side, or the surgeon may be a specialized consultant, collaborating with a surgery team on the patient's side. Since the introduction of minimally invasive robotic surgery,

From the [a]Resident in Ophthalmology, Henry Ford Hospital, Detroit, MI; [b]Medical Student, Oakland University William Beaumont School of Medicine, Rochester, MI; [c]Medical Student, Wayne State University School of Medicine, Detroit, MI; [d]Medical Student, Wayne State University School of Medicine, Detroit, MI; and [e]Chairman, Department of Ophthalmology, Henry Ford Hospital, Detroit, MI

* Address reprint requests to Man Li (Elina) Jin, Henry Ford Hospital, K-10 Ophthalmology, 2799 West Grand Blvd, Detroit, MI 48202

E-mail address: jin.manli.92@gmail.com (M.L. Jin).

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the concept of remote telesurgery has stepped out of the realm of fantasy and is instead becoming an increasingly likely reality in the future of surgery. Recent technological developments in teleoperated robotic systems and informational technology allows the surgeon to deliver expert care in remote locations.

Of the many advantages of telesurgery, one of the most important is providing access of high-level care to underserved areas and populations. For most of the world's population, access to surgical care is a luxury that most cannot afford, which disproportionately impacts those in developing countries. Approximately 2 billion people lack access to emergency and essential surgical care, most of whom are rural populations living in low- and middle-income countries.[1]

This leads to delay in care and often cumulates in acute, devastating life-threatening emergencies with consequences to both the patient and the health care system. A study found that less than 3% of the pediatric population in low-income countries and less than 8% in lower-middle income countries have access to surgical care.[2] For these pediatric patients, delayed or lack of care may contribute to premature deaths and chronic disabilities. Recognizing this lack of access as a global health issue, the World Health Assembly categorized emergency and essential surgical care and anesthesia as a component of universal health coverage.[3] Poor access to surgical care is far from an issue only of developing counties, however. In the United States, a nationwide shortage of surgeons to provide emergency general surgery has steadily worsened; a steady decline in the number of general surgeons proportional to the total United States population has placed an estimated 324 million Americans at risk of inadequate access to emergency surgical care.[4] While the US population has steadily increased and the need for access to emergency surgery has steadily climbed, the number of practicing general surgeons has remained stagnant at 17,000.[5] This leads to an increasing disparity of access to surgical care in rural communities. The number of general surgeons per population of 100,000 in urban areas (6.53) significantly outnumbers that of small/isolated rural areas (4.67).[5] Racial-ethnic and socioeconomic disparities are also apparent. Counties with higher percentile of African American and Hispanic populations have greater odds of not having a hospital with capacity for emergency surgery care, as do counties with higher uninsured populations, higher rates of poverty, and lower rates of college educated residents.[4] This disparity is even larger for surgical subspecialists, for whom there are incentives to stay in metropolitan cities for subspecialized job opportunities and access to large, academic institutions. The shortage of general surgeons in rural areas is worsened by the parallel trend of general surgery residents increasingly choosing to further subspecialize.[6] The result of this disparity is apparent: those who do not have routine access to surgery care whether due to distance, poverty, insurance, race, or economic status may delay treatment until an emergency requires surgical intervention, at which point morbidity and mortality may be markedly increased. On the other hand, doctors who decide to travel to rural areas to provide care often lack access to trained medical personnel and equipment, and often incur potential costs of travel as well as the risks associated with travel.

Efforts have been taken in the past to explore telemedicine and telesurgery to bridge the gap of access to surgical care. The first robot-assisted transatlantic telesurgery spanned 14,000 km between the surgery team in Manhattan, New York and the patient in Strasbourg, France; the procedure was a cholecystectomy which spanned 1 hour 54 minutes, with no significant complications or postoperative issues.[7] In 2003, the St. Joseph Hospital in Hamilton, Ontario and North Bay General Hospital in North Bay, Ontario, situated 400 km apart, established a telerobotic surgical service that aided rural surgeons in advanced laparoscopic techniques. In this study, 21 telerobotic laparoscopic operations took place, in which 2 surgeons operated together on 13 fundoplications, 3 sigmoid resections, 2 right hemicolectomies, 1 anterior resection, and 2 inguinal hernia repairs, none of which resulted in serious intra-operative complications or conversion to open procedures.[8]

Since the first telesurgery, other surgical specialties have explored the concept of telesurgery including neurosurgery, urology, otolaryngology, obstetrics, and gynecology. Most of the studies available in the current literature studying telesurgery is based on animal models and simulations.

Perioperative care

Preoperative and postoperative care can also be made more accessible through telehealth. In one study, audiovisual technology connected patients in Georgia with clinics operated by pediatric neurosurgery specialists from the University of Florida through virtual encounters. These specialists provided consultations for patients through the telemedicine clinic and ordered appropriate tests while trained nurses at the location of the clinic distributed care and facilitated referrals.[9] In addition, telemedicine has been utilized in studies of postoperative care for patients of surgical specialties. Multiple studies evaluating the use of smartphone images in postoperative care have showed promising results in monitoring postoperative complications such as wound infection and determining if patients needed further in person evaluation or treatment.[10,11] This allowed direct evaluation from the surgeon without incurring a visit to the emergency department or clinic. In another study, Hwa and colleagues employed telehealth in follow-up visits for more than 100 patients who underwent hernia repair and cholecystectomies, showing that a set of directed questions pertaining to wound healing and postoperative activity can be used to appropriately triage the patients into higher and lower risk groups. The higher risk groups were offered clinic visits with the surgeon.[12] These studies show promise for the future of safe postop follow-up through telehealth while minimizing complication rates.

Another benefit to telesurgery and perioperative telemedicine is the decreased financial strain for patients from travel-related expenses. In the Hwa and Wren study, more than 70% of the patients requiring post-operation visits had more than a 1-hour commute time, and more than 50% of patients had a round trip distance of more than 100 miles. Significant time and resources which would have otherwise gone into hour-long commutes were saved for the patient because of the telehealth visits.[12] Cota and colleagues demonstrated the potential for significant cost savings to the patient and health care system through telemedicine. They established a teleorthopedic service based in a tertiary referral center in which 921 patients in remote villages with acute orthopedic injuries were evaluated through email consults. Whereas all patients would normally be transferred to the tertiary center for orthopedic evaluation, this study resulted in 179 transfers while the remaining 731 patients were treated in their home communities. This incurred travel-related cost savings of more than $5.5 million Canadian.[13] If applied on a broader scale, the cost savings to the patient and health care system may be much more substantial.

Telementoring

Robotic and remote telesurgery has been readily applied to the field of surgical teaching in the form of telementoring. Developments in simulation technology have enriched the training options for the surgery trainee, while telementoring enhances the learning experience for surgical trainees by providing them firsthand experience in rare and complicated surgical cases under the expert guidance of specialists from remote locations. The United States faces the strain of a surgical shortage from a declining workforce of surgeons. The presence of telementoring may effectively increase the rate and volume of surgical education to alleviate the gaps of education left from the surgeon shortage. In addition, telementoring may help bring together multiple experts to focus on a single patient with a complex problem, even if they are located across vast distances. To assemble such a broad range of experts may be a logistic challenge in real life, but maturing communication technology has made that an achievable reality on the virtual plane. A study by Kunkler and colleagues on multidisciplinary team meetings for breast cancer patients suggests that telementoring may reduce the costs associated with transporting expert surgeons for training and in person consultation, making it cost-effective without sacrificing clinical effectiveness.[14]

The effectiveness of telementoring has been a topic of study in the current literature. A comprehensive review in 2013 was performed in 24 studies of telementoring, in which 433 surgical procedures were reported.[15] The primary focus of the studies was on surgical education.

Perceived usefulness of surgical telementoring was high among 83% of surgical trainees. Although only 23% of the studies systematically evaluated surgical performance in addition to educational outcome, all the studies reported improved surgical performance in trainees. A study by Ereso and colleagues reported the performance of general surgery trainees who were telementored and found significantly higher scores in tissue handling, instrument handling, speed of completion, and knowledge of anatomy in telementored trainees.[16] In 2019, a study by Erridge and colleagues reviewed 4 studies that compared telementoring against a complete absence of mentoring, in which 75% of the studies found outcomes demonstrating benefit as a result of telementoring.[17] The same study compared telementoring against traditional, in person mentoring. Out of 12 studies comparing the 2 methods, 58% showed no difference in outcomes, 1 found telementoring to be inferior compared to on-site mentoring, 1 found telementoring to be superior to on-site mentoring, and 3 found telementoring to have prolonged operative times.[17]

Prior to the emergence of telementoring, videoconferencing has been a tool widely used for medical education and collaboration by surgeons across the world. The improvements made in telecommunications makes telementoring a promising option to address the shortage of surgical specialists by improving adoption of new surgical technologies and expanding training options for the surgery trainees with minimal impact on the quality of surgery education.

Technology of telementoring

Telementoring can be further stratified by degree of involvement by the instructor. This may range from the most basic form of verbal guidance to physical participation by taking on the active surgery role using a robotic arm on the patient's side.

Videostream and verbal guidance

Verbal guidance involves a trainee performing surgery on the patient and a mentor providing oversight and verbal instructions using a live video stream of the operating field. This method of telementoring requires the least amount of equipment and setup. In addition to normal surgery set-up, the operating room is equipped with an external camera system and a microphone. The signal is consolidated in a computer with capabilities to stream audio and visual content to a computer in the proctor's office, which is equipped with a microphone to transmit verbal guidance to the operating room. The breadth of video input from the operating room may be expanded to include additional camera angles, fluoroscopic imaging, or any additional video data deemed necessary for the procedure. An additional camera may be set up in the proctor's office to allow 2-way audiovisual communication. This setup requires a capable telecommunication network that can transmit the large amount of data from the audio-video feed without significant delay. An advantage to this method of verbal guidance is the possibility of implementation with no additional dedicated hardware beyond what is already usually available in academic medical facilities. In addition, remote desktop software allows the mentor to access the video and audio communication on portable, personal computers at any location. The development of mobile robotic systems such as the Remote Presence RP-7 (In Touch Health, Santa Barbara, CA) allows the mentor to drive the robot with a joystick, and maneuver the digital camera on the robot's head to achieve real time, directed visualization of the surgical field.[18] The robot is fitted with a computer screen that allows visual communication with the mentor's side as well. Google Glasses (Google, Alphabet Inc, Mountain View, CA), a wearable visualization system equipped with a camera, microphone, and wireless network capabilities, is a newer technology that has been applied to surgery training (Fig 1). These glasses, when worn by the trainee, provide mentors with an unobstructed view of the surgery field from the trainee's point of view.[19,20] Improvements to video quality and battery life may make this technology a more reliable platform for telementoring.

Fig. 1. Google glass enterprise edition 2.[21] Glass wearable computing device is a trademark of google LLC.

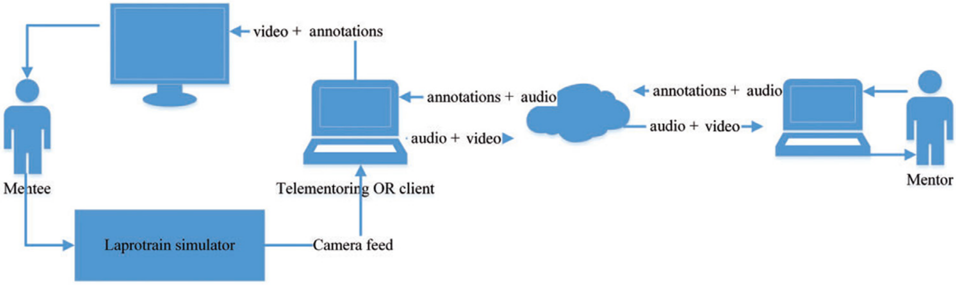


Fig. 2. Flowchart demonstrates the video and annotation flow within a system of telestration mentoring.[23]

Furthermore, the advent of modern communication applications like Skype and Zoom as well as the accessibility of highly mobile personal computers and tablet devices helps bridge the gap with easily accessible audiovisual transmission between mentor and trainee, bringing the possibility of reliable telementoring to the forefront of surgical training across the world.

Two-dimensional telestration

Two-dimensional (2D) telestration involves a higher degree of input from the mentor and interaction between the 2 parties. The visual feed from the trainee's side is transmitted to the mentor's computer, which is equipped with a telestration software allowing the mentor to create 2D illustrations and annotations on an overlay of the surgery field. The composite image is then transmitted back to a monitor in the operating room in real time. This provides the trainee with visual cues and specific, spatial instructions which, when combined with verbal instructions, has been shown to reduce the duration of the surgery and reduced student misunderstanding and need for clarification after starting the incision.[22] Telestration is especially useful for suggestions for identifying anatomy, teaching surgical techniques such as trocar placement, visualizing the laparoscopic procedure, and providing advice during the procedure. An illustration by Budrionis and colleagues (Fig 2) demonstrates an example of the video and annotation flow within a system of telestration mentoring. A drawback of verbal and 2D telestration telementoring is the

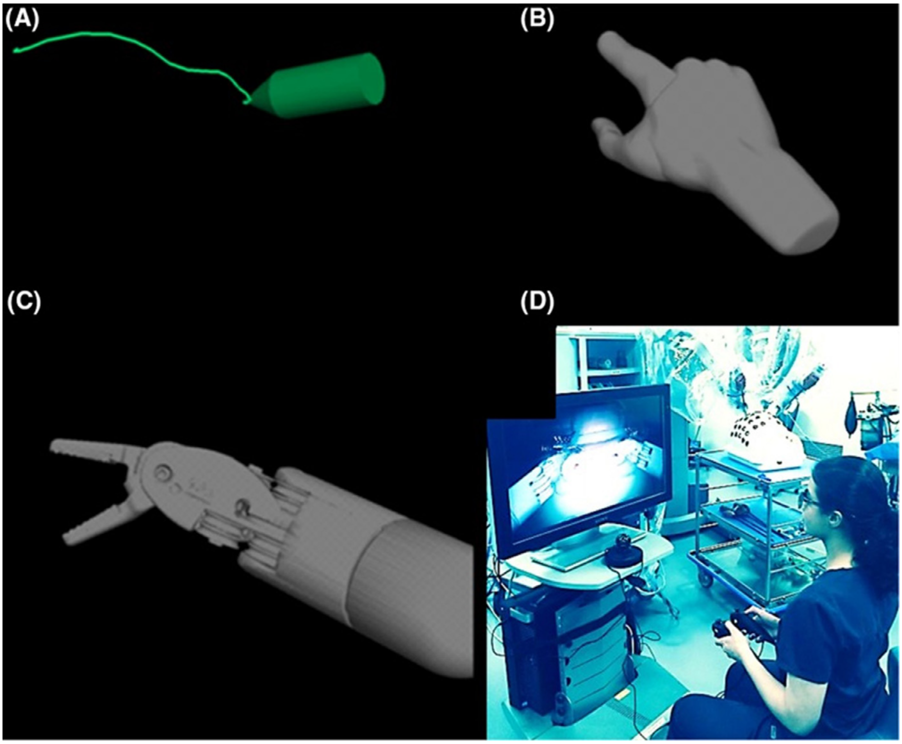


Fig. 3. Jarc and colleagues developed custom 3D mentoring software. Controlled by conventional video game controllers, remote mentors could overlay 3D pointers (A), 3D hands (B), and 3-dimensional (3D) instruments (C) on the surgery field videostream, which is then displayed to the trainee.[25]

inability for mentors to demonstrate movements with their hands during the process[23]; however, this could be easily mitigated using a 2-way videostream.

Three-dimensional telestration

Compared to the relatively mature technology of 2D telestration, 3-dimensional (3D) telestration is a new concept still in active development. Ali and colleagues developed a computer software that transforms input from the mentor's 2D annotations into 3D annotations by calculating the equivalent location of the 2D annotation in the vision from the contralateral eye and mapping it to a 3D point. The superimposed image is then transmitted to the trainee's view in the da Vinci (Intuitive Surgical, Sunnyvale, CA) robot's field.[24] In 2016, Jarc and colleagues developed a custom 3D mentoring software in which mentors used conventional video game controllers to manipulate "ghost tools" [25] on the surgery field videostream. These were semi-transparent overlays on stereoscopic, endoscopic images from the trainee's video input using the da Vinci surgical robot. The stereoscopic image with the ghost tool overlay was displayed back to the trainee using a 3D display software overlay, and to the proctor through a polarized 3D display. The study developed a 3D pointer, 3D control hands, and 3D instruments for mentoring, shown in Figure 3. The 3D pointer allowed proctors to draw and annotate in 3D. The 3D hands allowed the proctor to demonstrate positioning in 3D and illustrate grasping objects. The 3D instruments resembled real da Vinci surgical instruments and allowed orientation and positioning of the instruments as well as opening and closing the jaws to demonstrate grasping objects. The effectiveness of the

3D proctoring tools was compared to standard 2D telestration during dry-laboratory exercises using a standardized questionnaire, in which both proctors and trainees found the 3D instruments and 3D hands to be more effective than 2D telestration.

Telesurgery, telementoring, and telemedicine in surgical subspecialties

Neurosurgery

Telemedicine in neurosurgery has been shown to be beneficial to the field in both an efficiency and convenience standpoint. Telesurgery and telementoring are emerging fields in neurosurgery as studies have shown the marked efficacy of remote surgery and training novice surgeons. In addition, several reports have shown the potential for increasing efficiency and decreasing perioperative costs for both the patient and physicians through telemedicine.

Telemedicine can be a reliable alternative for neurosurgical consultations in areas where these services are limited. One study investigated a Georgia health district with establishing pediatric neurosurgery telemedicine clinics. Forty telemedicine clinics were held from August, 2011 through January, 2016, where a total of 40 patients were evaluated for diseases such as hydrocephalus, craniosynostosis, and myelomeningocele. Nurses in these clinics gathered history, performed physical and neurological examinations, and prepared patients for e-visits by the remote neurosurgeons.[9] The study proved to be effective in treating patients on an e-consult basis to meet the demand for expert pediatric neurosurgery care in an area with limited access.

An additional study investigated the socioeconomic benefits of telemedicine in pediatric neurosurgery clinics located in Florida. Clinic visits were from August, 2011 to January, 2017 and 55 patients were seen in a total of 268 follow-up appointments.[26] The average round-trip distance for a family from home to the University of Florida Pediatric Clinic location versus the pediatric neurosurgery telemedicine clinic remote location was 190 versus 56 miles, respectively. The families saved an average of 2.5 hours of travel time and 134 miles of travel distance per visit and the combined transportation and work cost savings for all visits totaled $223 per family and $12,048 for all families. The results indicate a substantial amount of both time and money saved by patients when utilizing a telemedicine-based approach for follow-up counseling.

Another study looked deeper into the cost-effectiveness of postoperative visits in patients who underwent neurosurgical procedures in West Bengal, India.[27] The model compared telemedicine care with a telemedicine center in West Bengal to an in-person postoperative care facility in Bangalore, India. Cost and effectiveness data relating to 1200 patients were collected for a 52-month period. The results showed that telemedicine was superior to an in-person facility care for post-neurosurgical procedures in utility and cost effectiveness. The telemedicine visits cost an average of 2630 Indian Rupees per patient whereas the in-person patient scenarios cost 6848 Indian Rupees per patient. Researchers attribute this stark difference in cost-effectiveness to increased patient volume utilizing telemedicine, success rate of telemedicine, and the elimination of patient travel.

Although the costs and convenience might make telemedicine the obvious choice for neurosurgical consults, there are concerns over feasibility of integration into practice. A review article of telemedicine in neurosurgery found that the biggest challenges in telemedicine in neurosurgery are the level of need for telemedicine services, maintaining patient confidentiality, and lack of interstate licensure reciprocity.[28] Telemedicine has much promise in the field of neurosurgery; however, there are still barriers to overcome when it comes to applying it to real-life practice in a safe environment.

A study investigated the effectiveness of using a TiRobot system (TIVANI Medical Technologies, Beijing, China)[29] to perform partially remote spinal fusion surgery. The TiRobot system is a remotely controlled surgery robot which can be used in full length spinal and orthopedics surgeries and is capable of advanced features such as accommodating and adjusting for patient motion. The study also used a 5G wireless network system for decreasing latency in the telesurgical procedures. In this study, a remote surgeon guided the TiRobot robot arm to locate and decide the position for pedicle screw placements in patients who require spinal surgery, while

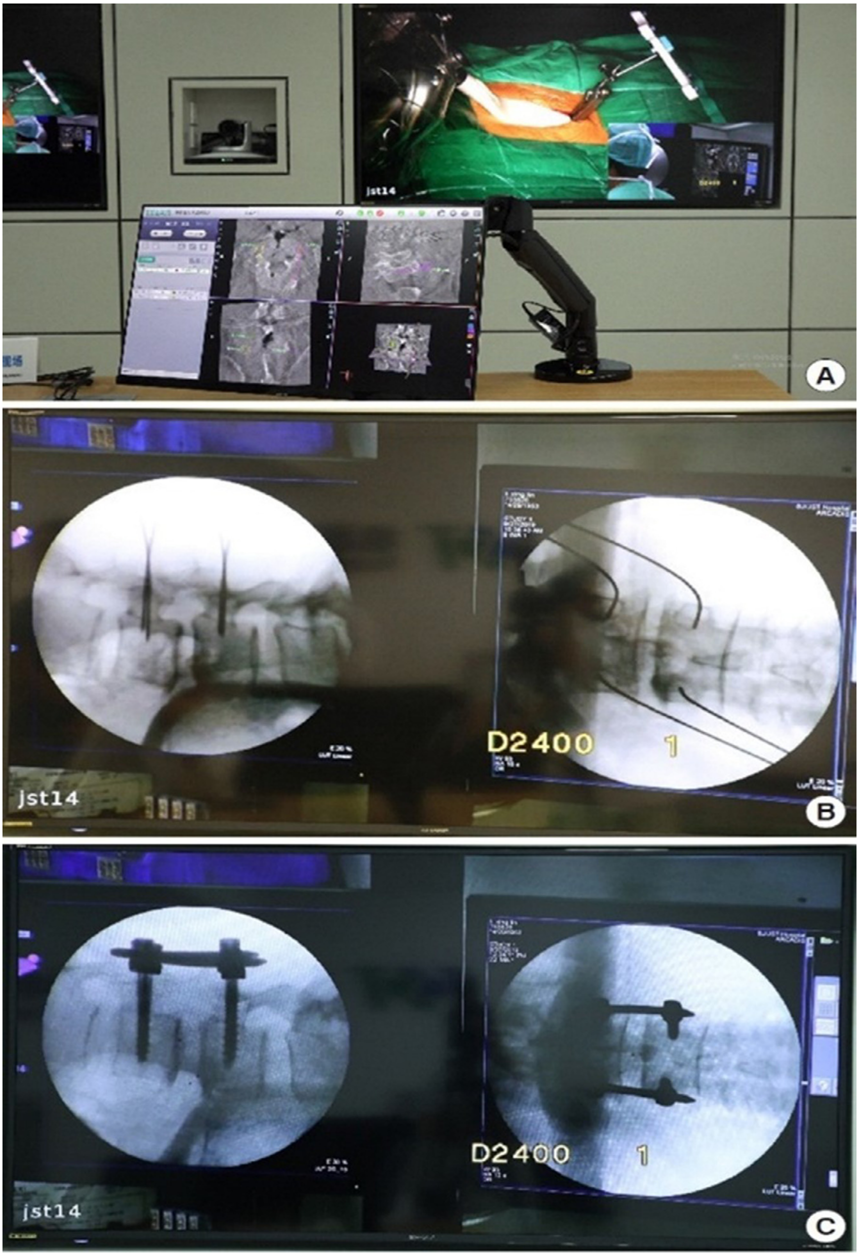


Fig. 4. The remote surgeon guided a robotic arm to manipulate pedicle screws to the planned location on the remote patient. (A) The remote workstation in the master control room with a view of the surgery field. (B) K-wire placement. (C) Screw placement.[29]

local surgeons completed the insertion at the planned location (Fig 4). A variety of spinal procedures were performed on 12 patients, including thoracolumbar fracture repair, lumbar spondylolisthesis repair, and lumbar spinal stenosis repair. Compared to previous studies, which were performed using 3G or 4G networking capabilities, researchers in this experiment utilized the novel 5G wireless system. During these operations, the mean latency was 28 milliseconds and no network adverse event was observed using the 5G network.[29]

In another investigation, Hongo and colleagues performed simulated minimally invasive operations using a telecontrolled micromanipulator system named the NeuRobot (Shinshu University, Matsumoto, Japan). This system was used to carry out surgical simulation of the opening of the Sylvian fissure and third ventriculostomy; the robot also aimed to remove a meningioma from a 45-year-old man.[30] These three operations were first carried out successfully in person to test the applicability of the robot in neurosurgical procedures. To test its applicability in remote operations, an in vitro simulation was performed on a rat brain remotely from a hospital 40 km away; the procedure was successful. In another study, researchers investigated neuro endovascular interventional procedures using a da Vinci system; these procedures are preferentially performed robotically amongst neurosurgeons to reduce radiation exposure to the staff.[31] Researchers developed a prototype of a support robot with 2 operators manipulating both the microcatheter and micro guide wire connected with the remote master driver with 2 joysticks; the design is meant to simulate catherization with both hands. The researchers aimed to study the reliability of the force gauge and the reproducibility of microcatheterization maneuvers into the experimental aneurysm using an in vivo silicone vessel model. Miyachi and colleagues concluded the system demonstrated accurate reproducibility of the operator's maneuver and was a safe operation in the vascular model.[31] They noted that this system could be a potential component for telesurgery in neurosurgery for neuro endovascular interventional procedures.

Mendez and colleagues investigated the feasibility of telementoring in the realm of neurosurgery. A robotic telecollaboration system capable of controlling movements of a robotic arm, providing audio and video communication between the mentor and trainee, and transmitting neuronavigational data (which can be used to construct a 3D image prior to the surgical procedure) was placed in the remote site for the telementoring procedures.[32] The communications were between a large academic center in Halifax, Nova Scotia and a community-based center in Saint John, New Brunswick, which was 400 km away. Long-distance telementoring was used in 3 craniotomies for brain tumors, a craniotomy for an arteriovenous malformation, a carotid endarterectomy, and a lumbar laminectomy. There were no surgical complications during the procedures, and all patients had uneventful outcomes. A survey of neurosurgeons in the remote location revealed that input from the mentors was useful in all of the cases.

Ladd and colleagues reported a proof-of-concept study demonstrating feasibility of 2D telestration mentorship in micro neurosurgical procedures using a microscope.[33] Students in the study were asked to identify 20 anatomical landmarks on a dry human skull to perform a craniotomy, with and without telementoring guidance from a neurosurgery resident. The resident was able to annotate directly onto a visual output stream to the operator's microscope. Afterwards, a senior neurosurgery resident evaluated the 2 groups of students on both timing and ability to complete a stepwise craniotomy. None of the medical students were familiar with the steps to complete a craniotomy prior to using the system. After telementoring, students were able to identify 100% of the structures and complete a craniotomy, compared to 50% (standard deviation 10%) before telementoring. The study ultimately showed the efficacy and value of telementoring for a neurosurgical procedure through a microscope. In another study, Mendez and colleagues investigated the use of telementoring to program implanted devices in neuromodulation. A remote-presence robot was used for remote programming; 20 patients were randomly assigned to either conventional programming or a robotic session.[34] The expert remotely mentored 10 nurses with no previous experience to program the devices of patients assigned to the remote-presence sessions. Mendez and colleagues observed no difference in the accuracy or clinical outcomes of programming between the standard and remote-presence sessions.

Obstetrics and gynecology

As a field that varies in practice, obstetrics and gynecology has the potential to greatly benefit from implementation of telesurgery and telementoring. Its use can save travel time and provide expert, specialized care to women living in rural or underserved areas.

Although robotic surgery is not uncommon in obstetrics and gynecology, the field has not yet taken the full leap to performing robotic-assisted telesurgeries. However, there have been a small number of reported cases of telesurgical scopes and biopsies. Specifically, the use of telecolposcopy has proven to be useful in rural areas with fewer numbers of trained practitioners. Colposcopy is a microscopic examination of the cervix after an abnormal Pap smear and it allows physicians to determine the need for cervical biopsy.[35] In early telecolposcopy use, still or video images were transmitted to another location for review; however, improvement in videoconferencing technology now allows for live interaction.[36,37] Remote colposcopists can view images in real-time and determine the need for immediate biopsies. They can also interact with the patient before and after the procedure.[37] With this decrease in image review time, it also allows the patient to receive biopsies at the same visit rather than returning later. Diagnostic outcomes were found to be similar to in-person colposcopies, but no long-term outcomes were followed.[38]

Although true telesurgical cases in the field of obstetrics and gynecology are limited, there has been more implementation of telementoring in the field. In 2002, Quintero and colleagues reported a case of a surgical operative fetoscopy completed via telementoring.[39] The patient was a 22 year old woman diagnosed with an acardiac twin pregnancy. The procedure—an attempt to occlude the blood flow to the acardiac twin—was completed in Santiago, Chile with telementoring from an experienced fetal surgery specialist in Tampa, Florida. They used panoramic cameras with direct image feed to transmit sonographic and endoscopic images, along with a teleconferencing system with video/sound. The procedure was completed successfully; however, the patient's postoperative course was complicated by vaginal leakage of fluid that eventually resolved spontaneously and the healthy twin was later delivered by cesarean section at 37.5 weeks.

While telementoring is useful during real-time operations, it also plays a role in surgical training. One example is a telementoring program focused on training gynecologic oncologists in the Republic of Mozambique, Africa.[40] Due to its lack of local health care resources, the incidence and mortality rate from cervical cancer in Mozambique ranks among the highest worldwide.[40] With the help of MD Anderson Cancer Center and several Brazilian physicians and researchers, Project Extension for Community Healthcare Outcomes (ECHO) was developed.[40-42] This telementoring program has held monthly videoconferencing sessions since 2015 to assist in training Mozambican physicians. Through these didactic lectures and case discussions with a multidisciplinary health care team, local physicians have gained a better knowledge of staging, surgical technique, and preoperative and postoperative care of gynecologic oncology patients. Although this telementoring project eventually evolved into several in-person training visits, these positive results indicate the benefit of telementoring in gynecologic surgery training.

Ophthalmology

Ophthalmology is a field of medicine which heavily utilizes physical examination and imaging modalities for management of a wide variety of eye diseases. As such, it has potential to greatly benefit from the advancement in artificial intelligence (AI) imaging technology and telemedicine. AI describes the design of technology to mimic human behavior. Deep learning is a branch of AI and machine learning that allows unsupervised learning using artificial neural networks.[43] It involves repeat comparison of the analysis output to a known standard, correcting itself if it deviates from that standard. Because of this, deep learning has gained attention in the fields of image and speech recognition.[44] Deep learning has been applied to ophthalmic imaging to diagnose and monitor common eye diseases, such as diabetic retinopathy, glaucoma, retinopathy of prematurity, and age-related macular degeneration.

Diabetic retinopathy is a complication of diabetes mellitus that causes irreversible damage to the retina. It is the leading cause of blindness in the developed countries and accounts for 17% of all cases of total blindness in the USA.[45] Approximately 12.2% of the United States population, representing 30.2 million people, has diabetes mellitus, and that number is expected to rise as its prevalence increases.[46] Vision changes may only develop later in the course of the disease, so the importance of developing cost-effective and accessible screening tools for diabetic retinopathy cannot be understated. Annual fundus examinations for patients with diabetes mellitus is recommended by the World Health Organization to prevent vision loss, but its implementation would amount to a significant strain on the health care system, which may not be sustainable.[47] Dilated fundus imaging may be obtained and reviewed by ophthalmologists for screening purposes; however, this could yield close to 1 billion images annually worldwide and carries the burden of requiring expert reading by trained personnel.[48] Several countries have adopted universal programs for routine telescreening of diabetic retinopathy, including England, Singapore, India, China, and the United States. In most screening programs, mydriatic retinal photographs are obtained by trained technicians in primary care facilities, transmitted via an online database and reviewed by trained graders. In the United States, the w largest diabetic retinopathy screening programs are the Joslin Vision Network and the Department of Veteran Affairs.[47,49]

The application of AI and deep learning to detect diabetic retinopathy from fundus imaging opens the potential for non-ophthalmologic providers to initiate diabetic eye screening. Patients who screen positive for diabetic retinopathy can then be appropriately referred to an eye care professional. Previously, automated grading systems have shown promise in performing "disease/no disease" grading for diabetic retinopathy.[50,51] Studies involving deep learning mechanisms in AI diabetic retinopathy screening demonstrate that the AI can reliably detect referable diabetic retinopathy (greater than mild disease) and have the potential to stratify disease severity.[47] An additional benefit to the electronic system is that the patient's information can be seamlessly integrated into a referral process and streamlines their experience from the initial screening encounter to evaluation by an eye specialist.

Retinopathy of prematurity (ROP) is a proliferative disease of the retina that can progress to scarring, tractional retinal detachment, and severe vision loss. The advancement of neonatal care has led to an increased survival of preterm babies and an increased prevalence of ROP. More than 15,000 children are blinded by ROP each year worldwide, making it one of the leading cause of childhood blindness across the globe.[52] As severe vision loss can be prevented with early intervention with laser photocoagulation or intravitreal injections, screening for ROP is routinely performed in premature infants worldwide.

There is a scarcity of pediatric eye specialists in the United states, and only 11% of all ophthalmologists are able to perform ROP screening examinations.[53] Thus, telemedicine becomes an option to give access of screening programs to medical facilities without an in-house pediatric ophthalmologist. Wide-field digital imaging have been used to evaluate pediatric patients for telemedicine ROP screening. Compared to serial indirect ophthalmoscopy, fundus imaging and telemedicine in ROP screening is superior in monitoring disease progression, facilitating second opinions, education, and research.[54,55] In the United States, the Stanford University Network for Diagnosis of ROP is a well-known telemedicine program established for ROP screening in at-risk infants, during which retinal images were obtained by trained nurses and evaluated by ophthalmologists. It showed 100% sensitivity and 99.8% specificity and captured all cases of treatment-warranted disease.[56,57] Since 2018, an AI system using deep learning algorithm called i-ROP has been developed for the detection of plus disease, a severe stage of ROP, and studies have shown that it may even perform better than expert human examiners in that regard.[58]

Glaucoma is characterized by the progressive loss of retinal nerve fibers and vision loss secondary to elevated intraocular pressures. It is the main cause of irreversible blindness, affecting 64.3 million patients aged 40 to 80 worldwide, and is expected to increase to 112 million by 2040.[59] The disease is often asymptomatic early on, and patients often notice visual changes and seek care in late staged disease. Thus, early screening and treatment for this disease has the potential to prevent significant vision loss in a large population. It is diagnosed through considering different parameters such as intraocular pressure, optic nerve appearance, visual field studies, and optic coherence tomography studies. This raises a unique challenge, as the diagnosis of early disease require expert interpretation of these studies from an ophthalmologist. Despite this, studies have shown that teleophthalmology can increase the sensitivity of glaucoma screenings in a primary care setting and extend care access to patients in rural areas.[60] In the largest tele-glaucoma study to date, 24,257 patients were triaged by optometrists in community clinics into 5 groups with varying degrees of severity and triaged the urgency for referral to a glaucoma specialist.[61] The resultant electronic medical record, including information regarding intraocular pressure and imaging and visual field studies, is reviewed by a glaucoma specialist. The study found that there was a substantial agreement between the optometrists and glaucoma specialists, and 13% of the optometrists' interim decisions were amended.[61] This study demonstrated the value of teleophthalmology and teleconsultations in expanding access to glaucoma screening and reducing the demand for appointments with glaucoma specialists, allowing medical resources to be directed to patients with the most urgent needs. In the past 20 years, teleophthalmology programs in the United States, Canada, and China have been developed and demonstrated the feasibility in detection and management of glaucoma.

Upon review of the current literature, there is still room for potential research towards the application of telesurgery and telementoring to the surgical procedures in ophthalmology. There are, however, challenges to telesurgery application in ophthalmology. The microscopic aspect of ophthalmic surgery is rather unique from other surgical specialties, which have the potential of integrating telesurgery into the application of robotic surgery. There is also the potential difficulty of translating the delicate movements of a remote surgeon into the microscopic operating field of the eye. On the other hand, the use of a microscope in the most common ophthalmic surgeries (e.g., cataract surgery and vitreoretinal surgery) gives the potential of applying telementoring directly to the surgeon's field of view, and future research could be directed to investigate an effective method for remote telementoring with this advantage in mind.

Otolaryngology

Surgeons in the field of otolaryngology have utilized robotic systems to assist with operations since the early 2000s. With the help of the da Vinci robotic system, surgeons are able to minimize neck incisions, with the first reported live case on a patient undergoing excision of a benign vallecular cyst in 2005.[62–64] Following this case and the concurrent evolution of robotics in the field of urology and cardiac surgery, Hockstein and colleagues explored the use of robotics in the pharynx and larynx on an airway mannequin.[65] Shortly thereafter, the first human trials of transoral robotic surgery were conducted and the trend has continued to expand to include oropharyngeal/laryngeal transoral robotic surgery and robotic thyroidectomies.[66] Although robotics have become more commonplace, few studies have described their use in long-distance telesurgery in the field of otolaryngology.[67]

To date, at least one case has proven the feasibility of telesurgery in the field of otolaryngology. A study by Klapan and colleagues described their experience with computer-assisted local and remote endoscopic sinus surgery in Croatia.[67,68] They noted that intraoperatively, staff and consultants can follow surgical progress on 3D computer models and consultations can be obtained from multiple locations.[68] Figure 5 shows an example of a 3D model of the cranial anatomy (A) and mapping of the operative field coordinate to the 3D spatial model (B), which helps surgeons navigate the surgical field prior to surgery.[68]

More recently, an experimental study was performed to evaluate the feasibility of remote robotic endonasal surgery. By completing both a local and remote removal of a phantom pituitary tumor, surgeons concluded that telesurgery over long distances was feasible with a robotic system.[69] The telesurgical endonasal tumor removal was done by a surgeon in Nashville, Tennessee, controlling a robot that was located in Chapel Hill, North Carolina (approximately 800 km away). They did not observe any discernable differences between the remote and local cases, both in terms of latency and qualitative feel of the surgeons who used the system.[69]

Although telesurgery in otolaryngology likely has yet to reach its peak, the use of telemedicine in preoperative and postoperative visits has been proven to be a useful tool in the field. In 2002, a prospective study on the use of ear, nose and throat telemedicine in remote military patients showed positive responses from both physician and non-physician medical personnel. Videoconferencing technology was used to evaluate specialty consults at international military treatment facilities and the study had a substantial clinical impact.[70] In fact, 45% of patients had a change in diagnoses following their telemedicine visit with ENT specialists vs general medical officers. This indicates a need for specialist consultation in this patient population and a direct benefit from telesurgery consultations.

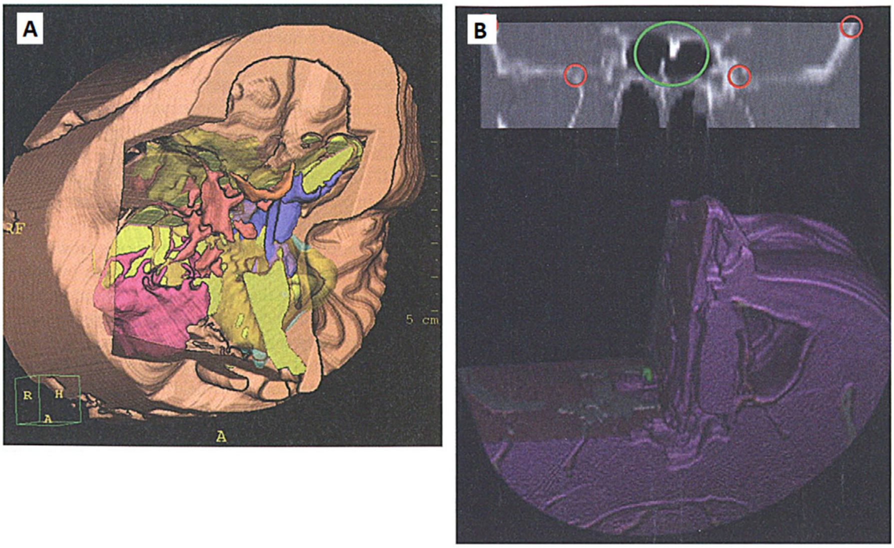


Fig. 5. (A) 3D model showing cranial anatomy and (B) mapping the operative-field coordinate to the coordinate of the 3-dimensional (3D) spatial model. These models allow surgeons to navigate the surgical field prior to the actual surgery and prepare for the procedure.[68]

A few years later, a study in pediatric otolaryngology showed similar positive results. Smith and colleagues measured whether or not there was agreement in diagnoses, clinical findings, and management plans in face-to-face versus videoconference consultations.[71] In fact, they determined that the recorded diagnosis was the same in 99% of cases and that surgical management decisions were the same in 93% of cases, proving teleconsultations to be an effective preoperative management strategy.

Finally, in 2018, Rimmer and colleagues conducted a retrospective chart review of completed telehealth visits, with 70% of the visits being postoperative encounters.[72] These encounters were completed via synchronous live videoconferences using computer and tablet technology. Most of the postoperative patients (57%) underwent neck surgery and 31% followed more extensive neck operations such as thyroidectomies, parathyroidectomies, dissections, and parotidectomies. The less extensive cases included styloidectomies, thyroglossal duct cyst excisions, branchial cleft cyst excisions, etc. For the majority of cases, patients completed a telemedicine visit at their second, rather than first, postoperative encounter; however, surgeons decided that a small number of patients who underwent less extensive surgery were able to schedule a virtual visit for their first postoperative encounter.[72] Patients were offered a post-telemedicine survey and results showed that 95% of patients reported satisfaction with the visit. The few dissatisfied patients attributed their dislike to wait time and technical issues. Regardless, the use of telemedicine in postoperative visits can be useful to minimize travel time, ease communication barriers, and provide meaningful clinical encounters.

Another area of growth in the field of otolaryngology is the use of telemedicine in surgical training. In 2016, a prospective case series was conducted to assess the efficacy of a telementoring program for surgeons performing endoscopic skull base surgery.[73] The program paired surgeons in Slovenia with an experienced skull base team at the University of Pittsburgh Medical Center in Pennsylvania through 2-way video and audio technology. This study was conducted over a 3-year period, with completion of 10 telementored endoscopic endonasal surgeries. They assessed outcomes by surveying participating surgeons and found that the technology was reliable, and it helped surgeons with no local experienced mentors develop their skills for complex surgeries. No patients had intraoperative complications; however, 2 cases developed

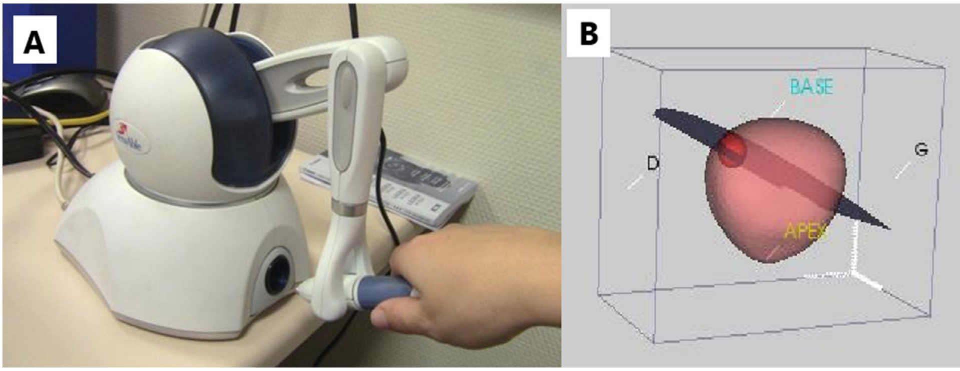


Fig. 6. (A) The omni phantom device is a haptic simulator with a motion tracker. The device stylus represents the ultrasound probe, while the device provides a constant force to replicate tissue friction. (B) The 3-dimensional representation of the prostate and the position of the probe plane.[78] This figure has been reproduced with permission from the institute of electrical and electronics engineers.

postoperative complications. One patient with a large olfactory neuroblastoma had a decrease in visual acuity following surgery and a patient with an olfactory meningioma experienced a postoperative cerebrospinal fluid leak that was successfully repaired endoscopically.[73] With reliable and available technology at most institutions, further studies should be conducted to gain a better understanding of the usefulness of telementoring in otolaryngology.

Urology

Although many surgical specialties are slower moving to adapt to telehealth changes, the field of urology has proven to adapt and innovate to match the pace of the surge in telemedicine. In fact, one recent article stated that pediatric urologists were among the first specialist to incorporate telemedicine into their daily practice.[74] Along with virtual routine office visits, urologists have implemented hospital rounds using robots and iPads (Apple Inc, Cupertino, California) and are even conducting postoperative care through telemedical interfaces.[74] Telesurgery and telementoring are also becoming more common in the field of urology.

Telesurgery in urology has grown in the past 20 years, with the first real telesurgical procedure performed in 1998. With communication between Baltimore, Maryland and Rome, Italy, surgeons were able to successfully gain percutaneous access of a hydronephrotic kidney using a surgical robot designed specifically for this purpose.[75,76] Even with a separation of 4500 miles, they reported minimal lag time between the surgeons hand movements, the robot's response time, and return of the video imaging.[76] This demonstrated the feasibility of urologic international telesurgery.

The first randomized control trial assessing the difference between human and telerobotic access to the kidney during a percutaneous nephrolithotomy followed in 2005. This group compared humans with robotic percutaneous needle access to local robotic with trans-Atlantic robotic percutaneous needle access on a kidney model. Although their results showed the robot was slower than human insertions, it proved to be more accurate.[77]

Another development in urologic telesurgery focuses on virtual reality as a means of improving surgical training. In 2013, a system was developed to map and target the prostate for simulation of transrectal guided prostate biopsies.[78] It allows resident trainees to practice surgical techniques as well as simulate various clinical scenarios that could occur during practice. It also gives them the ability to practice performing common operations using both video monitoring and other remote visual modalities that are becoming more popular in the telesurgery era. An image of the Omni Phantom Device (Delft Haptics Lab, Delft, The Netherlands) and the 3D representation of the prostate is shown in Figure 6.[78] Moving forward, 5 validated simulators have also been developed for surgical training of transurethral resection of the prostate using various surgical techniques; however, further studies should be performed to determine their efficacy and transferability of skills to real-world and telesurgical applications.[79,80]

Telementoring in the field of urology dates to a first case in 1996 reported by Moore and colleagues.[81] A novice laparoscopic surgeon was able to complete a varix ligation with the remote counseling of a more experienced surgeon who was located in the same hospital (1000 ft away). This was achieved through both video and audio conferencing, as well as remote control of the electrocautery unit. This initial case was the take-off point for other urologists to follow. This mechanism was later commercialized by the same group and tested using a greater distance between surgeons in the same city.[82]

Following this successful case, 17 more procedures were telementored between the 2 sites (9230 km apart). These procedures included 8 spermatic vein ligations, 2 retroperitoneal renal biopsies, 3 simple nephrectomies, 1 pyeloplasty, and 3 procedures to obtain percutaneous renal access.[75] With the help of 2 robots, audio and video connections, panoramic view of the operating room, and remote control of the electrocautery device, all of the procedures were accomplished with an uneventful postoperative course, although only 10 cases were successfully completed using telementoring.[75] In 5 cases, it was not possible to establish a connection and 2 cases needed to be converted to open secondary to intraoperative complications. Regardless, these results show the potential for promising telementoring cases in the future.

More recently, a study was performed to assess the utility of a web-based audiovisual telementoring system for robot-assisted radical prostatectomy vs direct in-person mentoring.[83] This system not only involved 3D, high-definition imaging of the operating field and room, but also allowed for annotation and 2-way audio feed between two separate institutions. As the first report of telementoring for robot-assisted surgery, they found that outcomes were comparable in terms of operating time, complication rate, and other parameters reflecting surgical success, demonstrating the potential of this system.

In 2004, a randomized control trial at 3 academic institutions was performed to assess the feasibility and outcomes of implementing robotic videoconferencing (telerounds) in urologic postoperative patients.[84] Using a remote-controlled robot with a microcomputer, video technology and audio capabilities at the patient's bedside, surgeons were able to interact with patients from a remote location. With enrollment of 270 patients, they found that patient satisfaction matched that of patients who received traditional bedside rounds and there was no difference between the 2 groups in terms of morbidity rate and length of stay. In fact, patients reported significantly increased satisfaction ratings in categories of perceived surgeon availability, quality of information received, and thoroughness. Two thirds of patients indicated that they preferred remote rounding with their own physicians rather than a physician partner at the bedside. Another study specifically on the use of tablet devices for telerounding illustrated favorable results, with 91% of patients reporting better care with tele-rounding and 97% agreeing that it should be implemented into routine postoperative care.[85]

Emerging technologies in telementoring

Virtual interactive presence technology

The basic premise behind the success of various forms of telesurgery is the concept of overlying multiple views of the surgical field to make a real-time collaborative operation. In 2D telestration, the endoscopic view is sent to the remote surgeon's screen. The remote surgeon can then begin to annotate directly on that view using various software. This annotated stream is then sent back to the local surgeon. This traditional telestration system uses the video directly from the endoscopic camera. A new technology named virtual interactive presence and augmented reality (VIPAR) recently conceptualized by Davis and colleagues seeks to make telestration telementoring more accessible using portable communication technology such as a commercially available tablet.[86]

Davis and colleagues conducted a study assessing the feasibility of VIPAR for performing endoscopic third ventriculostomy with choroid plexus coagulation in a telesurgical setting.[86] The

Fig. 7. Setup of local and distant stations for neuroendoscopy. The local station within the operative suite is depicted on the left and the setup for the distant station is shown on the right.[86] This figure has been reproduced with permission from Elsevier.

VIPAR software combines the visual feeds from the local station in Vietnam with the view from the remote station in the United States to form a single merged surgical field display. VIPAR introduces the major advantage of utilizing a real-time video display with annotations and diagrams from the remote surgeon overlaying the local surgeon's view. VIPAR uses a tablet display and an application called Lime (Lime Apps, Recoleta, Buenos Aires, Argentina). A tablet device is placed next to the endoscopy screen in the local surgeon's operating room. The local tablet captures the real-time surgical endoscopic view and sends it to the remote surgeon. The remote surgeon also has a tablet that displays the endoscopic view of the local surgeon. The camera in the remote tablet is pointed towards the remote surgeon's workspace, where he can make highlights or annotations. This information is then compiled into a single hybrid view and displayed back on to the iPad in the local surgeon's operating room via 3G and remote wireless networks. The remote surgeon is clearly able to delineate anatomic structures and accurately provide guidance to the local surgeon. This setup is shown in Figure 7. VIPAR is centralized around a proprietary software developed in C++ in Python programming language.[87] The program relies heavily on image capture, processing, rendering, and calibration. Since VIPAR runs on iOS6.0 (Apple Inc, Cupertino, CA) or later, the audio and 1080p high-definition video are displayed on tablets connected via wireless or 3G mobile networks. The study concluded that 15 endoscopic procedures were performed successfully with VIPAR guidance with no significant complications.

This study highlights an important advantage of telesurgery; the adequate accessibility of handheld devices, such as tablets and smartphones, allows for easy integration into health care systems through software applications. In contrast to the traditional 2D telestration models marketed in the literature, the VIPAR model is very accessible due to the availability of simple mobile devices with video capture capabilities such as tablets.[88] The simplicity and accessibility of the VIPAR system allows for a quick setup time of less than 10 minutes, which is comparable to, if not less than, setup times allotted for robotic procedures with long calibration processes. Furthermore, the VIPAR system is financially feasible for hospital systems as the total cost, including wireless data connection, is approximately $2,426 per year.[86]

The major drawback of a VIPAR type of technology is composite latency, or the delay in signal between the remote and local stations. Fiberoptic cables are commonly used for telecommunication to provide high speed data connection between buildings. Despite the use of a direct fiberoptic cable connection between the local and remote stations, the study estimates 75.5 millisecond of lag time.[86] Although Wirz and colleagues found that a latency time greater than 300 milliseconds can produce inaccuracies in instrument handling, Korte and colleagues concluded that latency times less than 2 seconds allot for clinically acceptable operations to be completed.[69,89] Although studies have shown an average latency ranging from 237 to 760 milliseconds with the VIPAR technology, surgeons noted no interference in the performance of the procedures.[86,87] Some surgeons at the local site reported purposeful slow surgical movements to allow the remote surgeon to make up for the short latency time. Local delays from image processing and fluctuating remote delays from internet transmission speeds can be shortened by using faster networks, such as 5G mobile data and fiberoptic internet.[29] Another downside of the VIPAR technology is the limited use to only endoscopic, endovascular, and microsurgical procedures. VIPAR relies on a surgical view displayed on a screen; it would be difficult to mount a tablet in a position to capture a real surgical view with high quality resolution while also not interfering with the local surgeon's apparatus. This is where devices such as wearable augmented reality can provide clinical utility, although with increased costs.

Wearable augmented reality

Traditional forms of telesurgery between a local and remote surgeon relied on an annotated video displays from the remote surgeon, which is then interpreted by the local surgeon and applied to the actual surgery. However, this method presents major drawbacks in that the local surgeon must play a balancing act of shifting his/her attention between the video screen and performing the surgery. Furthermore, the burden of correctly analyzing the annotated video display and overlaying it over the patient's anatomy falls upon the local surgeon. The solutions that came next included tablet displays that are placed between the surgeon and the local site, such as the VIPAR. This system combines the information from both surgical sites and automatically overlays the sensory input upon one another. The disadvantages to this system are that the tablet can often obstruct the local surgeon's view and limit the surgeon's workspace. Additionally, utilizing a 2D display on a tablet degrades the surgeon's depth perception due to loss of stereopsis. Hence, the newest promising research in telesurgery surrounds the idea of wearable augmented reality headsets as they provide a real-time 3D view of the local surgical site while also incorporating audio and visual input from the remote surgeon.

Shenai and colleagues conducted a study utilizing a form of wearable augmented reality that was combined with virtual interactive presence (VIP).[90] This form of VIP consists of the local and remote station each equipped with a binocular videoscope for the local and mentor surgeon (Fig 8). The device allows the surgeon to visualize the remote field, the local field, and the surgical field of common interest. The remote and local views are compiled into one stream via a remote direct memory access connection, which displays the combined view on a computer screen. On this common field of interest, the remote surgeon may point to anatomical landmarks and annotate the surgery field directly to the local surgeon (Fig 9). The surgeons can secure the

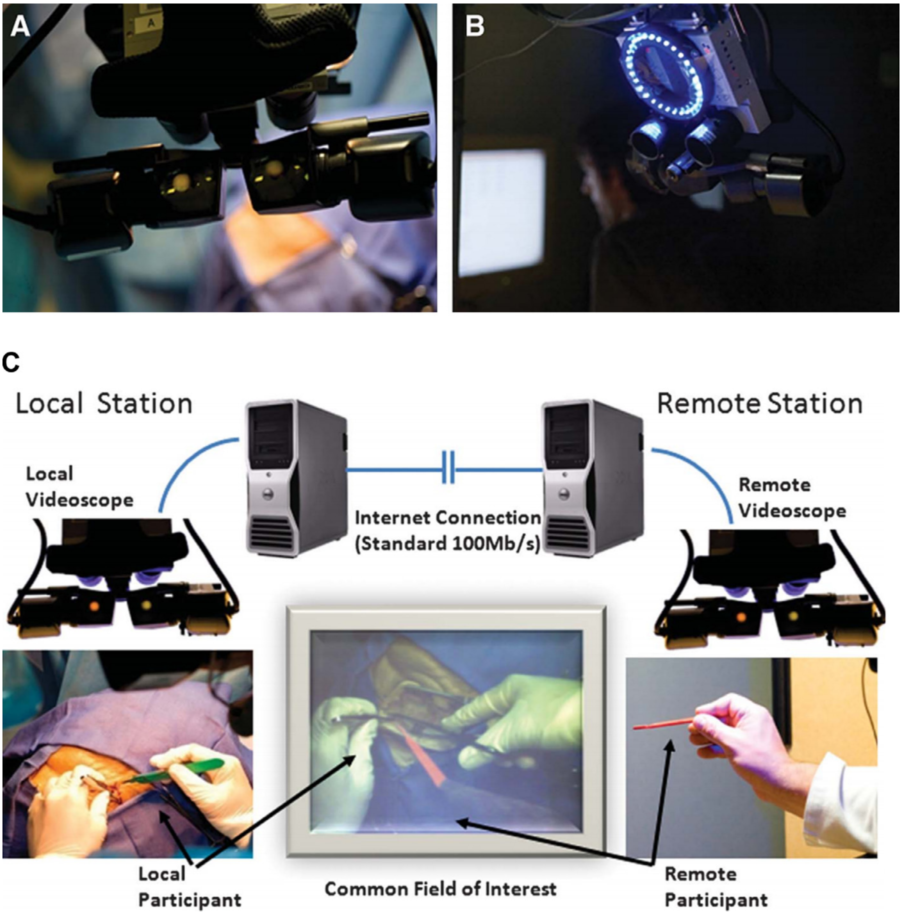


Fig. 8. Binocular videoscope. (A) high-definition binocular viewer allows participants to view composite field of interest. (B) Two 1.3-megapixel cameras, situated at a customized distance, capture the local and remote fields. The remote videoscope contains a circular blue light-emitting diode (LED) array to for background subtraction.[90] This figure has been reproduced with permission from Oxford University Press. (C) "Schematic diagram of virtual interactive presence and augmented reality system. The local participant and local elements are physically present in the field of interest (i.e., local station). The remote participant is not physically present in the field of interest. Local and remote videoscopes capture the local and remote fields of interest, respectively, and provide a point of view for local and remote participants. Each participant views a common field of interest, composed of differing combinations of local and remote elements or participants.[90] This figure has been reproduced with permission from Oxford University Press.

videoscope to his/her head and wear it like spectacles with a microscopic view through each eye. The videoscope also can be mounted by a mobile steel arm, to relieve the weight on the surgeon's head. The device is equipped with a fully functioning microphone and headset, which allows for direct communication between the remote and local surgeons. In contrast to previous forms of VIP, this system allows for multiple remote surgeons to participate in one local operation. Another advantage of this device is the ability to integrate the video display with pre-surgical radiographic imaging, a feat that has not been achieved previously in the field of telerobotic surgery. The major caveat is that each remote station must have a fully equipped room with a videoscope and computer screen. Shenai and colleagues tested the feasibility of this technology by overlaying a non-contrast magnetic resonance imaging of the head onto the carotid endarterectomy surgical view, in order to visualize the spatial anatomy in greater

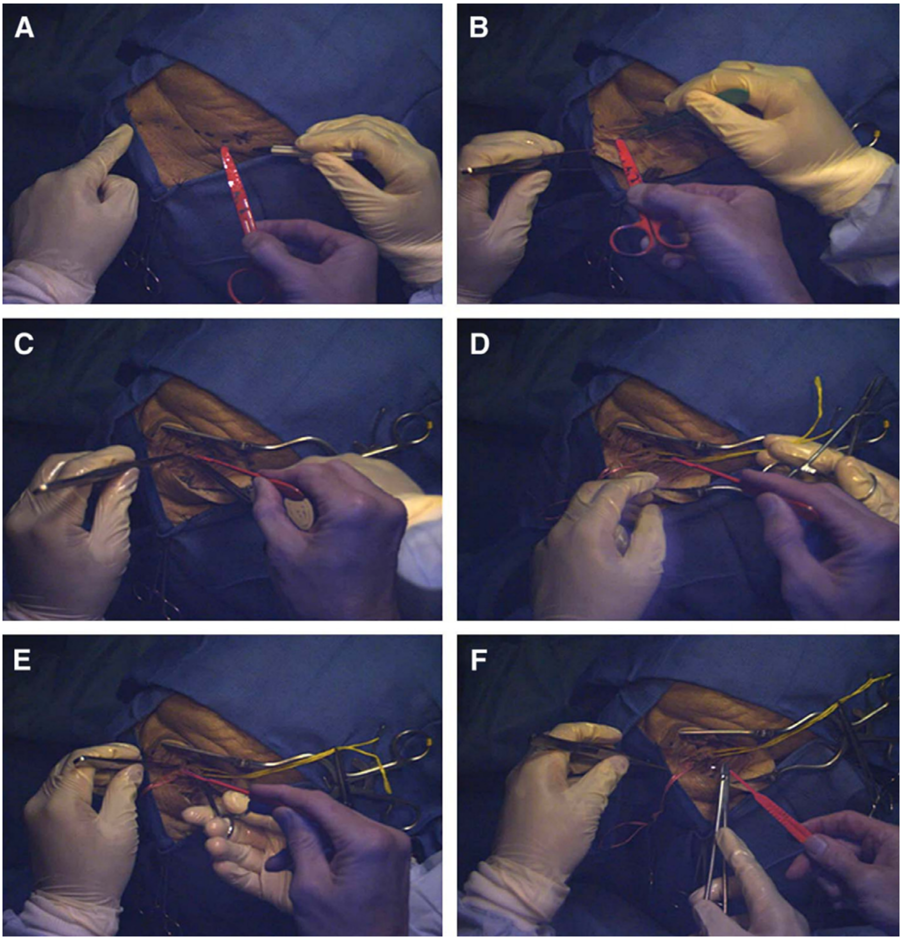


Fig. 9. A-F demonstrate steps of a carotid endarterectomy. Ungloved hand is the remote surgeon's hand (holding a red pointer) as it appears to the local operator during guidance and training.[90] This figure has been reproduced with permission from Oxford University Press.

detail.[90] This feature may improve surgical precision and accurate correlation with anatomical structures, which in turn could potentially lead to better surgical outcomes. Interestingly, this study concluded that the delay between the 2 sites was due to the slow camera refresh rate as opposed to the network connection latency, which is the more commonly reported cause of delay in VIP studies.[69,86,89] However, the surgeons here also concluded that the delay was not clinically significant and did not negatively impact the surgery in any way. The remote surgeons commented on feeling surgeon fatigue due to a lack of tactile feedback through the VIP system.

One of the most commonly used technologies in telementoring has been live videoconferencing, similar to the VIPAR technology described above. However, the success of telesurgery performed in these cases is dependent on the ability of the local surgeon to apply the directions given by the remote surgeon to the real-time surgical field. Furthermore, the local surgeon must continuously look back and forth from the screen to the surgical field.[91,92] In an attempt to resolve some of these issues, Liu and colleagues and Munoz and colleagues created a wearable Microsoft HoloLens device that integrates an augmented reality system.[93,94] Microsoft developed a HoloLens device that enables manipulation of holograms and 3D imaging as if they are real

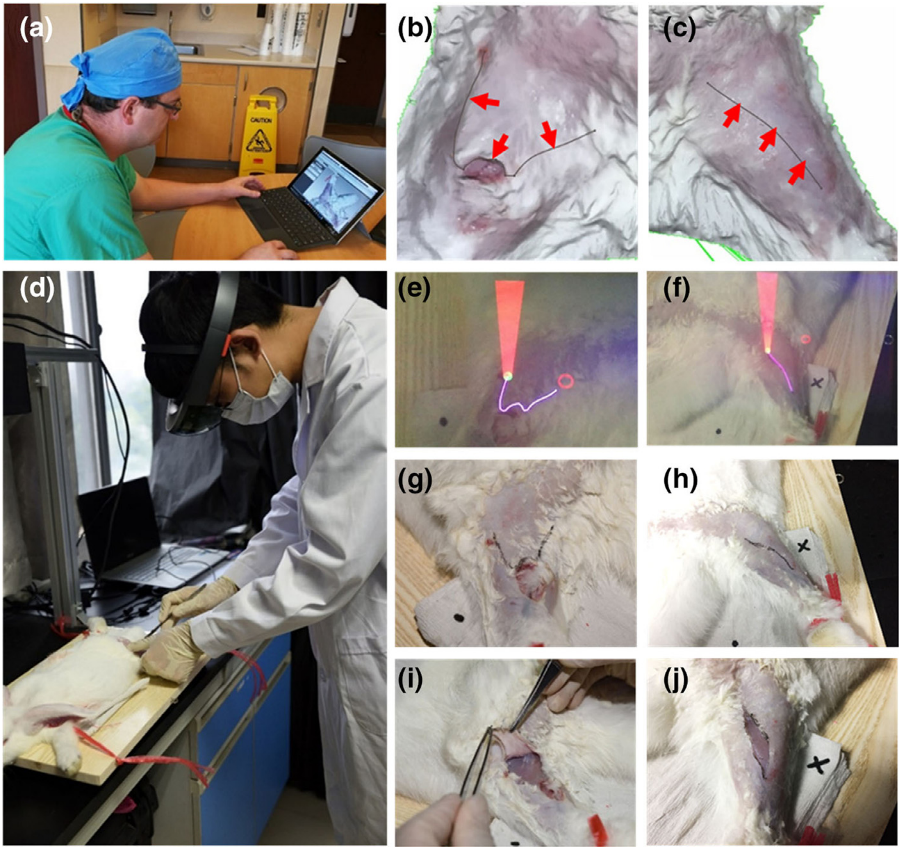


Fig. 10. The simulated skin grafting surgery and fasciotomy carried out on a rabbit model under the guidance of the HoloLens based telementoring system. (A) An experienced surgeon at OSWMC is watching the 3D model of the thighs and drawing the optimal trajectories for skin grafting surgery and fasciotomy. (B) and (C) The 3D models of the left and the right thighs and the annotation guidance by the experienced surgeon at OSWMC are transferred back to the HoloLens device at USTC for guided skin grafting surgery and fasciotomy, respectively. The black curves pointed by red arrows show the optimal surgical trajectories defined by the experienced surgeon at OSUWMC. (D) An inexperienced trainee wearing the HoloLens device is carrying out the surgical operations. (E) and (F) The HoloLens device displays the actual surgical scene superimposed with the augmented reality scene for skin grafting (left) and fasciotomy (right) operations. (G) and (H) Following the virtual scalpel guidance, the trainee draws the predefined trajectories in black ink on the left and the right thighs for grafting and fasciotomy surgeries, respectively. (I) and (J) The actual dissected skin tissues for skin grafting and fasciotomy operations.93 OSWMC, Ohio State University Wexner Medical Center. USTC, University of Science and Technology of China. This figure has been reproduced with permission from Springer Nature.

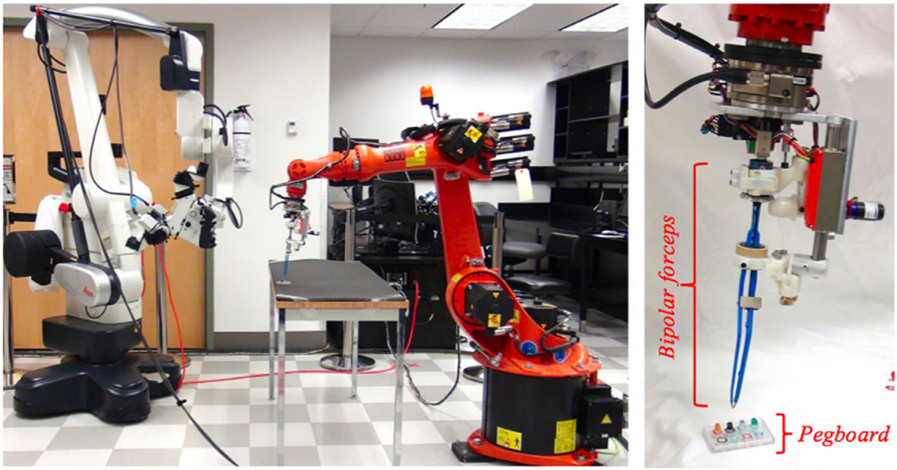
objects. The augmented reality setup allows for the 3D position of the scalpel to be tracked by a stereo camera and wirelessly transferred to the wearable HoloLens device. The geographically remote mentoring surgeon can demonstrate complicated incisions and surgical maneuvers on a virtual image, which is stored by the 3D stereo camera. This video captures fine details (up to 2 mm), such as the exact path, length, and depth of the cut.[95] This virtual 3D image is then co-registered with the surgical field and displayed on the HoloLens device worn by the local surgeon who is performing the operation in real-time. This allows for the placement and anchoring of 3D images into the local surgeon's field of view without encumbering the surgeon's workspace or needing to look at a separate screen. A demonstration of this setup is shown in Figure 10.[93] Another advantage is that the 3D augmented reality system has the capability to save these videos, which can be used for teaching purposes in future operations. Benchtop in vitro models have proven feasibility by successfully performing procedures such as skin grafting and fasciotomies, which require a great level of precision due to surrounding neurovascular structures.[93] Additional studies found that the wearable augmented reality device decreased focus shifts and placement errors amongst local surgeons compared to the typical telestration technique of utilizing a separate video screen to communicate between the local and remote surgeons.[94] Although the HoloLens configuration combined with augmented reality software has the potential for clinical utility, a few issues still remain as a barrier to widespread implementation of this technology.

Latency times and unstable network connections between the local and remote surgeons are limiting factors to the recent developments in telesurgical platforms. Anderson and colleagues investigated a future step visualization add-on to the already established STAR (system for telementoring with augmented reality), which can provide pre-recorded telementoring services via an annotated tablet display.[96] The tablet overlays a pre-recorded video of an experienced surgeon performing the same procedure in a step-by-step manner. The tablet is placed between the surgeon and the patient, acting as a window in which the surgeon can view the surgical site, the annotated video instructions, and his/her own hands and surgical instruments. The local surgeon can adjust the brightness and transparency level of the instructional video depending on the lighting in the operating room. Although this system can help assist local surgeons when there is an unstable network connection or when there is a lack of experienced surgeons at the remote site, the possibility remains for misalignment of the video display from the actual surgical field due to variant human anatomy. Furthermore, these pre-recorded instructional videos cannot predict unforeseen events that occur during the procedure; hence, the videos are likely not a stand-alone replacement for a remote surgeon's presence. With further reiterations and versions of the wearable augmented reality devices being developed, this form of technology could provide benefit for patients, surgeons, and the overall quality of health care.

Haptic feedback technology

The dynamic interaction between the surgeon and the operative field is a critical component behind the art of a surgical procedure. For surgeons to become more comfortable with telesurgery, haptic feedback technology is potentially an effective and reliable way to provide valuable tactile feedback to the learning surgeon. Since a haptic system enables the surgeon to feel the tensile strength, depth, and texture of the surgical tissue without being in the operating room, it has been a promising area of research.

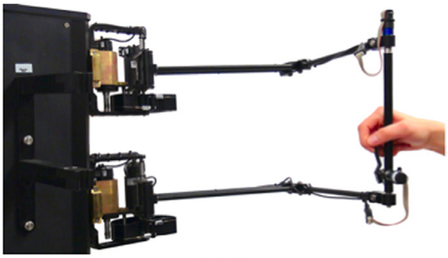
Surgeons have been developing and testing haptic devices such as the PHANToM Premium 3.0 (3D Systems Inc, Boston, MA) and the Haption haptic feedback hand-controllers (Haption, Aachen, Germany).[97] Zareinia and colleagues provided a telesurgical setup with a remote station and a local station, connected over a wired local area network. The remote station contained a hand controller haptic device. As the surgeon made movements on this haptic device, a KUKA KR-6 manipulator (KUKA Robotics, Augsburg, Germany) at the local station mimicked the same motion on the real surgical site (Fig 11). The KUKA manipulator then sent feedback signals back to the remote surgeon regarding the forces applied on the surgical tool and properties of the objects at the local site. A surgical microscope provided a 3D visual display, so the surgeon was able to visualize the surgical field. Figure 12 shows the haptic feedback devices tested in this study. Although the surgeons in this study were performing micromanipulation "peg-in-hole" tasks rather than operating on in vitro tissue, a similar setup can potentially be used to integrate haptic feedback devices into an operating room system. There are multiple haptics devices available on the market, and they each vary in their capability of force feedback and positional sensing, measured in degrees of freedom. Notably, the Maglev 200 commercialized by Butterfly Haptics (Pittsburg, PA) offers unique advantages as a device that relies on Lorentz levitation rather than the traditional mechanical hand controllers. Lorentz levitation utilizes the force of a particle traveling in an electromagnetic field to position and orient a rigid object.[98] In the context of telesurgery, this device offers zero static friction, zero mechanical backlash, high position resolution, and wide stiffness range.



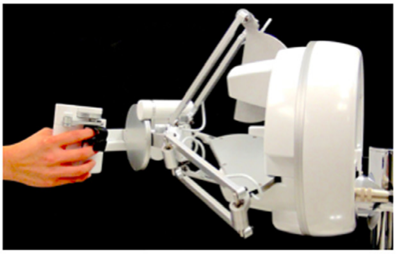
(a) (b)

Fig. 11. (a) Tele-operated Kuka KR-6 (KUKA Robotics, Augsburg, Germany) robot (right) and surgical microscope equipped with 2 high-definition cameras (left) used to perform a peg-in-hole task. (b) roll and actuation mechanisms for bipolar forceps.[97] This figure has been reproduced with permission from John Wiley & Sons Inc.

(a) PHANToM Premium 3.0



(b) HD²



(c) Sigma 7

Fig. 12. Haptic feedback devices tested in a study by Zareinia and colleagues.[97] This figure has been reproduced with permission from John Wiley & Sons Inc.

Many robotic surgical systems are equipped with built-in haptic feedback devices. For example, the neuroArm has been used in many neurosurgical cases ranging from image-guided stereotaxy to microsurgery.[99] The system consists of a mobile base with mounted robotic manipulators, such as bipolar forceps and a suction tool. These manipulators are controlled by a main system controller, which is also connected to a sensory immersive workstation that includes haptic hand controllers and 3D monitors. Although Sutherland and colleagues used this robotic device to perform glioma resection with a local surgeon, the neuroArm can be

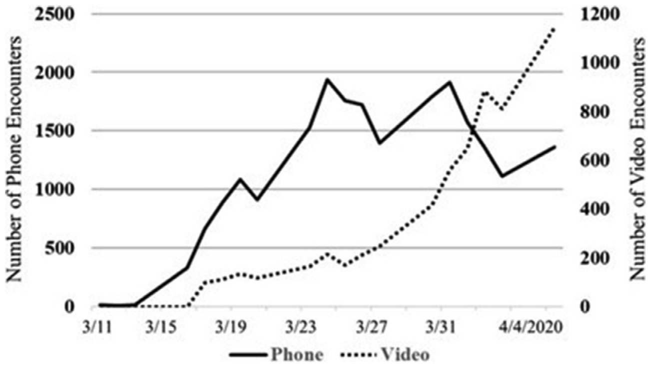


Fig. 13. Increasing trend in telephone and video encounters between doctors and patients since the advent of the coronavirus disease 2019 pandemic.[100] This figure has been reproduced with permission from Springer Nature.

extrapolated into a telesurgical field with the use of high-speed local area network or even 5G network devices with minimal delay latencies.[29]

Network connections and accessibility

One of the biggest advantages of implementing a telesurgical model is the accessibility and ease of a strong network connection with powerful bandwidth. The current technology climate has seen drastic improvements in 5G networking and access to smartphones, tablets, and Wi-Fi/local area networks. In fact, Tian and colleagues were able to show 5G networks can serve as a strong enough stand-alone connection to reliably assist in neurosurgery from a remote location.[29] A limiting factor to the telesurgical model is the latency in audio/video signal transmission, with previous studies showing a latency time greater than 330 milliseconds can worsen surgical outcomes.[86,87] However, in a case series of 12 reports, the 5G network was found to have strong bandwidth connection with a mean latency time of only 28 milliseconds.[29] The 5G network connection is also particularly compatible with the da Vinci robot, which is commonly used throughout many specialties such as urology, cardiac surgery, and hepatobiliary surgery.

Over the years, the field of telesurgery has taken off due to the rapid developments of VIP, augmented reality, and wearable technology devices. The literature has reported numerous telesurgical models that have shown potential in achieving surgical precision and clinical effectiveness. With new avenues for 5G networking and high-speed fiberoptic internet, the technology is continuously being improved and slowly being implemented in the safest manner for patients.

Coronavirus disease 2019 (COVID-19)

Telemedicine

The COVID-19 pandemic has drastically changed the face of patient encounters, highlighting telemedicine's potential to continue providing quality care to patients in the face of strict social distancing restrictions. Contreras and colleagues found that, within days of enforcing restrictions on in-person clinical encounters, the number of telemedicine visits increased dramatically from 100 telemedicine visits per day to 2200 at Ohio State University Wexner Medical Center (Fig 13).[100] They further surmised in the coming years that both telemedicine and telesurgery will continue to be popular options due to interconnected consumer health devices and 5G data connectivity.[100] Telemedicine helps curb infection spread and increase efficiency in delivering healthcare during the COVID-19 pandemic. Mihalj and colleagues reported the use of telemedicine in preoperative assessments of patients.[101] Before their planned operations, patients at home can perform a self-assessment of their temperature, blood pressure, and heart rate; furthermore, doctors can examine a patient's skin for any usual rashes or lesions using image transfer or a videoconference. It is even possible to remotely monitor blood sugar, blood pressure, electrocardiogram, and heart murmurs with the help of electronic health devices at home.[101] More importantly, screening for COVID-19 symptoms remotely rather than in person can reduce the chance of putting others at risk. The patients were also remotely triaged into higher and lower risk groups before admission to the hospital through assessing risk factors, such as cardiovascular and pulmonary disease.[101] This can then accelerate the admission process and ensure that higher risk patients can receive close monitoring and care.

Some studies have explored the public's reception of telemedicine visits. Kapoor and colleagues conducted a retrospective review of outpatient records from March to April, 2020 to determine the "show" rate of patients who were offered a telemedicine visit in place of an already scheduled face-to-face outpatient visit to a pediatric ophthalmology clinic.[102] A total of 237 virtual ophthalmology consult visits were offered, of which, 212 were scheduled and 206 were completed. This resulted in a no-show rate of 3% in scheduled clinic e-visits, highlighting the efficacy of virtual encounters and the willingness for patients and their families to utilize telemedicine during the COVID-19 pandemic.[102] Taken together, this paints a trend of acceptance of telemedicine as the emerging norm of practice during the COVID-19 pandemic and suggests that patients are willing to consider the option for telemedicine in place of in-person encounters. Khairat and colleagues conducted a cohort study of confirmed COVID-19 cases in patients using a virtual urgent care center in North Carolina.[103] As of March 18, 2020, the clinic treated 92 confirmed COVID-19 cases in a total of 733 virtual visits. Of the total visits, 257 (35.1%) were related to COVID-19-like symptoms.[103] This suggested that telemedical care may help reduce emergency room visits, conserve health care resources, and curb the spread of COVID-19 by treating patients remotely.[103]

Telesurgery

Performing emergency surgery on a COVID-19 positive patient requires proper protective equipment to limit the exposure of medical staff to the absolute minimum. De Simone and colleagues published a review on the impact of the COVID-19 pandemic on the management of acute abdominal emergencies and recommended that surgery should be postponed if possible. If not, staff in the room should be limited to a minimum and proper protective equipment should be donned.[104] Interestingly, their recommendation regarding the use of laparoscopy in COVID-19 patients is to proceed cautiously only if absolutely necessary, as there is a risk of introducing the virus from release of gas from the pneumoperitoneum. It is in these scenarios that perhaps telesurgery may be introduced to minimize staff exposures. Al Mazeedi and colleagues report on an emergency surgery for a COVID-19 positive patient who developed superficial thrombophlebitis of the cephalic and basilic veins of his left arm that eventually necessitated surgical drainage of a loculated foci of infection.[105] The operation was performed by a junior attending surgeon, while an augmented reality telesurgery platform called "The Proximie" was used by 2 remote consultant surgeons, who were able to telestrate on the operative field on the screen to give suggestions for proposed incisions. The report by AlMazeedi and colleagues reaffirms the potentially powerful role telesurgery may play during the COVID-19 pandemic to maximize patient outcomes while minimizing staff exposures to the virus.

Telementoring

The COVID-19 pandemic has affected medical training significantly, particularly in surgical fields. Bernardi and colleagues researched the impact of COVID-19 on general surgery residency training in Italy and observed a marked decrease in number of operations performed by postgraduate year-6 residents, noting a decrease from 36.2 operations in the January-March, 2020 period to 14.0 operations in March-May, 2020.[106] This decrease was largely attributed to the cessation of elective operations and significant reduction in emergency room visits. The study found that there was a 50% decrease in total operations performed by Italian resident physicians due to the COVID-19 pandemic. Aziz and colleagues conducted a national survey for general surgery residents in the United States on the impact of COVID-19 on their surgical training.[107] A survey of 1102 residents reported a significant decline in hands-on surgical training and showed that much of their education shifted to online didactics. In another survey, Ferrara and colleagues hoped to gauge the possibility of reshaping surgical training for ophthalmology residents to help answer the decrease of surgical training.[108] From a total of 504 responses from 32 different countries, there was a strong consensus in use of web-based case presentations (91.7%), web-based discussion of edited surgical videos (85.7%), and simulation based practice in surgical training (86.9%) during this time of decreased surgical volume.[108] A survey of 933 Italian resident physicians in the field of obstetrics and gynecology found that 54.7% of residents reported a significant decrease in training activity, 69.5% of residents managed COVID-19 positive patients directly, and 59% believed that their training was irreversibly compromised.[109] In another study, Khalafallah and colleagues reported the impact of COVID-19 on the neurosurgery department at Johns Hopkins.[110] Between March, 2020 and April, 2020, the number of pediatric operations decreased from 15 to 3, while the number of in-person neurosurgery clinic visits decreased by 97.12%. They also noted that neurosurgery education shifted from in-person sessions to videoconference sessions. In the era of COVID-19, there is a strong demand for virtual-based surgical training and telementoring to ensure effective surgical training regardless of the specialty.

Challenges

The advent of the COVID-19 pandemic has initially overwhelmed many health care networks and revealed many areas of potential improvement in our health care system. The primary purpose of virtual health care services during the COVID-19 pandemic was to reduce staff exposure to ill patients, preserve personal protective equipment, and minimize the impact of patient surges on health care facilities. This certainly does limit the spread of the virus, but it may come at a cost to those who do not meet the prerequisites to take advantage of telemedicine. A National Health Service digital figure showed that nearly 40% of individuals had no access to online consultations at all in 2019 [111]; that population may lack access to adequate health care in an advancing telemedical society. This highlights an emerging problem in telemedicine and telesurgery where the effects of the pandemic are creating a health inequality that disproportionately affects the older population and those of lower socioeconomic status.[10] Other limitations include the inability to perform physical examinations online, which could lead to missed diagnoses and proper assessment of first-time patients.[10] Despite all the potential challenges in the way, telemedicine will no doubt continue to grow and become more integrated into the core of modern medicine, even in the post-COVID era.

Challenges ahead

Legal and ethical concerns

Although the ability to perform remote surgical procedures and provide telementoring across the globe has many positive effects, this variability in location also poses some legal challenges. Regulations and licensure can vary by both state and country, but even in the United States there are no clear regulations on licensure for telementoring and telesurgery.[112,113] Multiple models have been proposed, such as treating the patient as if they are in the location of the physician for the duration of the interaction (allowing them to abide by the physician's geographic licensure).[112] However, current approaches lean more towards treatment of the patient based on the patient's location, rather than the physician's.[114,115] As laws differ from state to state and even worldwide, regulations are needed for more concrete definitions of the increasing use of telesurgery and telementoring.

Additionally, legal concerns and the implications of litigation/responsibility become blurred when a surgeon is not physically present during a surgical case. If an internet connection is disrupted or lost, there is no prevailing rule for who is held legally responsible.

The ethics behind this responsibility can also be extended to patient consent. Currently, no standard operating procedures exist for proper patient consent of telesurgical procedures.[112] Defining each telesurgical case and informing the patient that multiple surgeons may be involved in their care is essential to ethically and accurately obtain patient consent, especially if they are being treated by surgeons operating from remote locations.

Privacy concerns

With the advancement of technology and storage of protected health information on virtual platforms, there is always a concern for possible breach of patient privacy. In the realm of telesurgery and telementoring, care is heavily reliant on the network connections, which in turn provides the opportunity for leakage of sensitive patient health information. A major concern in this field is its potential for cyberattacks.[112,113] Whether it be the interference of internet connection during a surgical operation or hacking for the purpose of collecting protected patient information, considerations must be taken during any telesurgical procedure to protect the patient. One study focusing on cyberattacks on teleoperated robotic cases found that most attacks were on network and communication connections.[116] The most concerning aspect, however, was the potential for robotic function to be completely taken over by an outside party or hacker.[116] Although there are no official cases of this occurring in practice, engineers were able to breach security and manifest system-wide attacks during an experimental study.[116] Although encryption can provide security against leakage of sensitive patient information, these results illustrate the need for backup systems in case of cyberattack.[112]

Latency and connectivity

With any new technology, challenges may arise in the form of connection, user error, or signal delay. In terms of telesurgery, these challenges should be taken into consideration regarding patient safety. Often, there is a lag between the surgeon's movement and the appearance of that movement on the console. This lag, or intrinsic latency, can result in an increase in surgical errors.[89,117] Specifically, a study at the Center for Minimal Access Surgery using surgical simulation determined that a latency of 135 to 140 milliseconds was noticeable, yet could be accounted for safely with surgical adaptation.[117] Any latency more than 800 milliseconds make telesurgery more difficult and potentially unsafe for the patient.[117]

In terms of telementoring, these difficulties in connection or latency can also become a barrier to safe surgery. Bove and colleagues reported that in a study of 17 telementored surgeries, 5 cases could not be completed due to inability to establish connection with the remote site.[75] Establishing and safeguarding a strong connection between the primary and remote locations is one of the major challenges of providing telementoring and should be considered when planning telementored procedures.

Cost and financial considerations

Because robotic and telesurgical equipment is still relatively new in multiple surgical fields, start-up expenses for telesurgical programs can be quite costly. Surgical equipment aside, reliable network telecommunication is also a concern, especially in more rural, underserved areas.[112] These regions can benefit most from telesurgery and telementoring; however, purchasing the necessary equipment is still possibly an insurmountable barrier to its implementation. One study in Romania showed that the cost for creating and maintaining a functional telesurgery program for 1 year is estimated at 903,111 Euros (more than $1,078,820 US Dollars).[118] A less recent study in the United States also estimated robotic machine costs at approximately $1 million and the cost of maintaining telecommunication lines between $100,000 and $200,000.[119] However, the savings for health care systems that these programs could provide have not yet been elucidated.

Financial considerations between patient and surgeon

Additionally, in telementored surgical cases, yet to be clarified is the financial relationship between the patient and the telementoring physician. There is discussion on allowing the telementoring physician to bill as a second physician vs bundled payments that redistribute funds to compensate multiple physicians.[112] In Virginia, state legislators specified that payments are highly dependent on the degree of involvement from each attending physician and their role in the operation.

Financial policies and barriers

When it comes to telehealth coverage, reimbursements vary on a state-to-state basis. One example is the state of Virginia, which has incorporated telemedicine as a whole (not just telesurgery) into their Medicaid budgeting; however, the cost of providing telemedicine service or other technical fees is not included in their allowance.[120] By 2017, most states (all except Massachusetts and Rhode Island) had some reimbursement for telehealth services through their Medicaid program; however, many of these policies were vague, used broad language, and did not specify the role of telesurgery specifically.[121]

Additionally, nationwide barriers exist for patients over 65 years of age who are covered by Medicare, as this program places restrictions on the types of telemedicine services covered and has variable cost increases or inadequate payment.[121] Although most states offer reimbursement for telehealth visits, including postoperative care, telesurgery initiatives are not quite there yet. Moving forward the cost for providing telesurgical care is highly dependent on ever changing health care policies and will likely be a major focus of future policies.

Author's contribution

Man Li Jin: Conceptualization. Investigation. Project administration. Writing- Original draft preparation. Writing – Reviewing and Editing. Meghan Brown: Data curation. Writing- Original draft preparation. Dhir Patwa: Data curation. Writing- Original draft preparation. Aravindh Nirmalan: Data curation. Writing- Original draft preparation. Paul Edwards: Conceptualization. Supervision. Writing – Reviewing and Editing.

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