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Dynamics and organizations of telesurgery

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Dynamik und Organisation der Telechirurgie

Zusammenfassung. *Grundlagen:* Laparoskopische Chirurgie und Telekommunikation haben die Vorraussetzungen für Telechirurgie geschaffen.

Methodik: Review der Literatur und Darstellung eigener Erfahrungen.

Ergebnisse: Heute kann Chirurgie über große Entfernungen durchgeführt werden und ermöglicht spezielle chirurgische Versorgung von Patienten in entlegenen Regionen, wo eine entsprechende chirurgische Versorgung nicht vorhanden ist (verletzte Soldaten am Kriegsschauplatz, Astronauten im Raumschiff). Durch die Revolutionierung des Internets ist es vorstellbar, dass sich ein Patient bei einem Spezialisten einwählt und dieser dann den Eingriff mit einem ferngesteuerten Operationscomputer durchführt. Telechirurgische Teams sind derzeit damit beschäftigt, ein weltweites Telechirurgienetz einzurichten.

Schlussfolgerungen: Wenn Telechirurgie aus sozialen, kulturellen, politischen und wirtschaftlichen Gründen nicht überall möglich sein wird, besteht doch kein Zweifel, dass sie eine besondere Bedeutung im 21. Jahrhundert haben wird.

Schlüsselwörter: Telechirurgie, da-Vinci-Operationsroboter, Computer-assistierte Chirurgie.

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Summary. *Background:* The dawn of laparoscopic surgery and the telecommunications revolution have given birth to the field of telesurgery.

Methods: Even now, surgery is being performed over great distances to bring expert surgical care to physically isolated patients with otherwise limited healthcare access.

Results: As technical obstacles are eliminated in the future, telesurgery will extend the reach of military surgeons to patients at sea and on the battlefield, and astronauts will undergo procedures performed by earthbound interventionalists. Just as the Internet has revolutionized the way everyday consumers shop, eventually, telesurgery may transform surgical care, as patients may stay in their local hospitals and simply "dial up" the best telesurgeon for their specific operation. Telesurgical teams have now formed to refine technical approaches to telesurgery, study the effects of telesurgery on human task performance, and establish telesurgery networks around the world.

Conclusions: While some legitimate social, political, and economic issues remain as impediments to the routine practice of telesurgery, there is now no question that telesurgery will play a role in the delivery of surgical care in the twenty-first century.

Key words: telesurgery, round-trip delay, control latency, da Vinci surgical system, computer-assisted surgery.

Background

Telesurgery has the potential to connect expert and subspecialist surgeons to patients located in isolated areas where access to major medical centers and/or specialty care is difficult to achieve. In the future, providing surgeons the ability to mentor and perform procedures from remote locations will have a profound impact on the quality and type of care available to patients in rural settings as well as in extreme and remote environments such as the battlefield, at and under the sea, and in extraterrestrial locations [1]. While telesurgery is very much in its infancy, the technological advances in video and computer communications made over the past 25 years have paved the way for this exciting new field. The ability to capture, compress, enhance, and transmit digital video, voice, and end-effector control data over long distances provides the technology necessary to make telesurgery a reality. However, the 1990s' revolution in surgery focusing on minimally invasive and laparoscopic technology provided the paradigm shift necessary to make telesurgery a practical possibility [2]. By physically disconnecting the surgeon from the patient, the surgeon could only visualize the operative field by means of technology. The interjection of technology between the surgeon and the patient also meant that surgeons could no longer depend solely upon their hands to operate [3]. Laparoscopic instruments and the inherent limitations thereof inspired industry to develop surgical robots. These computer-assisted telemanipulators when combined with the advanced telecommunication technology available today constitute the tools of the modern telesurgeon.

Defining “telesurgery”

Because the effective communication of telesurgery concepts is paramount to the success of the field, and because the word “telesurgery” is often used to mean many different things, an early definition of relevant terms is critical. Generally speaking, “telesurgery” is used to describe two concepts, the latter being a subset of the first. The first “loose” definition of “telesurgery” is the use of telecommunication technology to aid in the practice of surgery [4]. This encompasses everything from pre- [5], intra-, and postoperative teleconsultation and tele-evaluation, to intraoperative telementoring, teleproctoring, and telemonitoring [6], to telemanipulation and telepresent robotic surgery. Because the ultimate goal of research in the field of telesurgery is performance of surgery on patients whose location is geographically distinct from that of their surgeons, our group prefers to limit the definition of “telesurgery” to the remote performance of robotic surgery over telecommunication lines [7].

Technical issues

An overwhelming goal of telemedicine has been to replicate on-site activity from a distance. Much of what is measured in telemedicine and judged successful focuses on how faithfully and without incident these replicated activities duplicate their on-site equivalents. For this reason, several technical terms that affect telesurgery require definition [7].

Control latency indicates the delay between when a remote surgeon moves a controller and when the surgical tool actually moves inside the patient. This time is the sum of the delays inherent to digitization of the controller movement, transmission of these digital signals to the patient's location, and electro-mechanical translation of these signals.

Visual discrepancy indicates the delay between when an object moves in the operative field and when the surgeon visually appreciates such movement at the remote location. This time is the sum of the delays inherent to digitalization and compression of the video signal(s) by the coder-decoder(s), transmission of the signal(s) across telecommunication networks, and decompression of the signal(s) by the remote coder-decoders.

Round-trip delay is the sum of control latency and visual discrepancy, i.e., the time between when a remote surgeon moves a controller and when such translated movement is visually appreciated at the remote location.

Jitter means the real-time variations in the amount of delay introduced by variable traffic in telecommunication networks.

Bandwidth is a data transmission rate indicating the maximum quantity of information that can be transmitted through a given communications circuit per unit of time. In telesurgery this is the amount of video, voice, and control data that can be transmitted back and forth – measured in kilobits or megabits (1000 kilobits) per second.

Quality of service (QoS) indicates the degree of guarantee of or commitment to a particular quality of network service, including a defined minimum rate of data delivery (bandwidth), as well as maximum intervals between information packet delivery. Telesurgery, which is particularly sensitive to network delays, is greatly affected by this parameter. QoS is lowest over the public Internet and is highest when using dedicated communication assets such as ISDN and ATM networks. Increasing QoS increases the cost of the telecommunication link.

The team

In its current state, the pieces that make up telesurgery are complex, expensive, and somewhat fragmented. Thus, to successfully engage in telesurgery – whether clinically or in the research arena – investigators must pull together material resources (surgical robots, telecommunications equipment, animal surgery facilities, etc.), technical expertise (technology support), clinical motivation and material (cases or the potential thereof), and financial support (grant funding). The task of amassing such resources is typically beyond the capability of any individual or single institution. Therefore, the development of an effective telesurgery program generally requires formation of a multi-institutional telesurgery team. The telesurgery work performed by our group has occurred as a result of the collaborative interaction of two university medical centers (University of Cincinnati and Johns Hopkins University), two clinical military medical centers (Walter Reed and Malcolm Grow), a Silicon Valley-based surgical robotics company (Intuitive Surgical), and a telemedicine funding agency (TATRC). Each institutional member of our team provides unique resources – material, manpower, financial, or otherwise – essential to the success of our telesurgery program. Administration of such a diverse network of participants spread out across the North American continent is a challenge and is successful only because each institution and individual team member is working toward a common goal of routine efficacious clinical telesurgery. Obviously, effective communication between team members is essential to this effort. Not surprisingly, our group has found the use of E-mail and periodic teleconferencing indispensable in achieving this end.

Current approaches

Clinical applications of telesurgery have thus far been based on the Zeus robot (which is no longer commercially available) and have depended primarily on high-bandwidth, low-latency, high-QoS telecommunications services [8–10]. The largest published series of clinical telesurgery cases to date comes from Canada, where low population density and the presence of many isolated rural communities are combined with a nationalized healthcare system and a sophisticated federal telecommunications network to create the ideal environment for the routine clinical application of telesurgery and telesurgical mentoring [11]. The network used in this telesurgical practice is a 15 megabit per second (15 Mbps) virtual private network (VPN) with high-priority guaranteed QoS. Recognizing that wide adoption of clinical telesurgery in higher-population-density locations such as the United States and Europe is cost prohibitive using such expensive connectivity, and that "heroic" use of telesurgery in bandwidth-poor extreme environments such as the battlefield and outer space is not possible with such robust data rate transfer requirements, our group has focused on lower cost, lower bandwidth applications of telesurgery [12].

Our approach is also different in that we have based our work on the commercially available da Vinci surgical robot platform. We have recently performed telesurgical nephrectomies in a porcine model between Sunnyvale, California and both Cincinnati, Ohio, and Denver, Colorado, using the public Internet with no QoS guarantees (Fig. 1) [13]. These experiments represent the first telesurgery in the United States, the first telesurgery using the da Vinci surgical system, the first stereoscopic telesurgery, the first robotic collaborative telerobotic surgery (i.e., both local and remote robot surgeon consoles were used), and the first telesurgery over the Internet using nondedicated bandwidth.

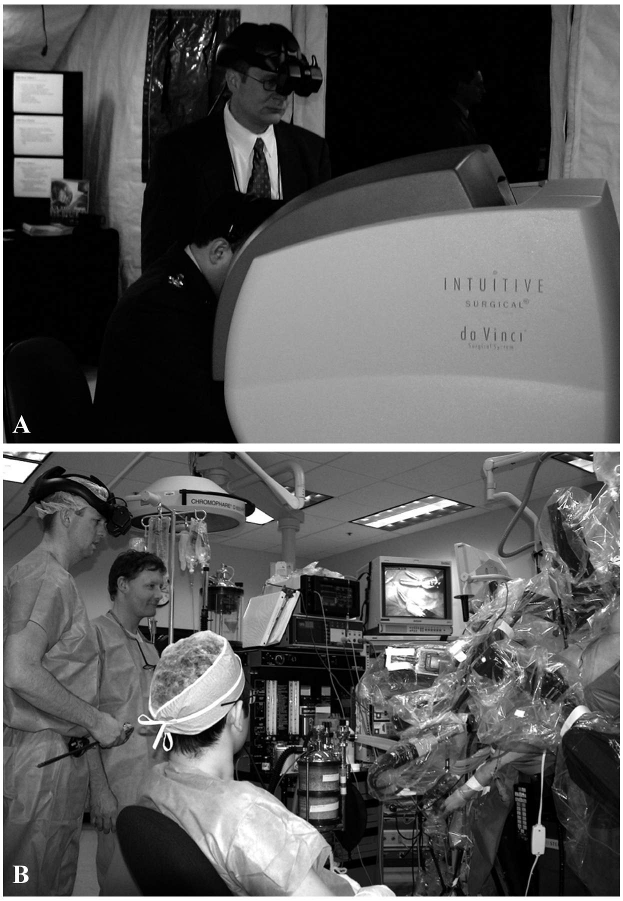

Fig. 1. Telesurgery using the da Vinci surgical system. Surgeons in Denver, Colorado (**A**) operate on a pig in Silicon Valley, California (**B**) through the Internet

Lessons learned

Our work in this area has taught us a number of valuable lessons. Serial improvements in our approach to the telecommunications link in our experiments (decreasing robotic control data transfer rates, eliminating unnecessary video channel bandwidth use, etc.) confirmed for us the importance of nonhuman laboratory groundwork when establishing a telesurgical practice [14]. This is one specific reason why intermural resource sharing is so important in this field, as it is not cost-effective for a single institution to dedicate to research multiple million-dollar surgical robots to facilitate investigator rehearsal and perfection of various telesurgical communication links [15, 16].

One very simple aspect of collaborative telesurgery which, when optimized, we have found to have a profoundly positive impact on telesurgery success is reliable, clear, and low-latency two-way voice communication. We take for granted on a daily basis our ability to consult with colleagues over the telephone in real time [17]. When voice communication in the setting of telesurgery is suboptimal over an Internet designed for asynchronous data transfer, we have found that redirecting voice communication through standard landline or cellular telephones greatly improves the effectiveness of telesurgical collaboration at negligible cost.

While relatively inexpensive from a monetary perspective, pushing the low-bandwidth envelope in telesurgery does not come without cost. The telesurgeons in our experiments experienced round-trip delays in the 500–900 ms range. This is significant delay compared to the high-fidelity French and Canadian experiences which publish delays in the 100–200 ms range [8, 11]. Low-fidelity connectivity also leads to increased packet loss, which, in extreme circumstances, produces video of such poor quality that greater delay is actually preferential.

Because lower cost telesurgery currently means higher delay telesurgery, we have investigated in great detail the effects of such delay on surgical task performance [18]. We have found that, while delays of 500 ms (1/2 second) do produce a significant degradation in human task performance, a number of compensatory mechanisms can be capitalized upon which make telesurgery possible even in the 1000 ms (1 second) delay range (unpubl. data). Slowing surgeon hand movement greatly reduces the incidence and degree of "overshoot" that often occurs when operating with delay. Furthermore, with practice, surgeons learn to anticipate the new location of their instruments, creating "virtual instruments" in their minds which correlate, to varying degrees, with the actual positions of the instruments rather than the visual representations of the instruments. Repetitive movement within the operative field (such as occurs with respiration, cardiac contraction, and vessel pulsation) sometimes makes the actual location of the tissues difficult to ascertain when operating with delay. Decreasing ventilatory rate can help with this problem, and computer-assisted gated movement promises to eliminate this issue in the future. When performing telesurgery in a collaborative environment, allowing the remote surgeon (and therefore the delayed surgeon) to perform tasks which require relatively less precision (such as retraction as opposed to cutting) facilitates progress in an environment with significant delay. With regard to stereoscopic telesurgery, the use of a video synchronizer which delays one channel by up to a frame to allow a delayed frame from the other channel to "catch up" eliminates the severe degradation in performance experienced with intraocular discrepancy. Finally, while not practical for urgent or emergent surgery, scheduling telesurgical cases for low network traffic times may improve the quality of the telecommunications link.

Extreme environments

The future application of telesurgery for patients in extreme environments is currently providing a great proportion of the driving force (i.e., funding) behind the development of telesurgery. While it will always be an option – however socially stressing – for patients requiring routine, elective operations (e.g., antireflux procedures) to travel to major medical centers for their care, time and cost often prohibit evacuations of soldiers, mariners, submariners, and astronauts from their extreme environments to undergo urgent or emergent surgery [19, 20]. For now, it is these patients who stand to gain the most immediate tangible benefit from the advancement of telesurgery. As technology costs are reduced in the future, telesurgery may improve access and quality of care for needy patients in underserved extreme developing environments as well.

Future networks

As telesurgery gains acceptance within the surgical community, we envision medical center networks of telesurgeons and remote telesurgery suites. The use of ubiquitous telecommunication technology will make access to telesurgery (and thus access to expert specialty surgical care) a more financially viable reality for patients in rural communities. While the architecture for telemonitoring is already in existence, a number of technical, social, and legal barriers will need to be overcome before routine clinical telesurgery becomes widely adopted.

Conclusions

In summary, telesurgery is an exciting new discipline emerging from the marriage of surgery and telecommunications that promises to greatly broaden the scope of practice of expert surgeons [21]. Because telesurgery is resource intensive, research and development in this field is best suited to a team approach. As telesurgery teams refine the technical threshold parameters for bandwidth-minimum telesurgery, learn how to optimize human interaction dynamics in the tele-environment, and train their surgeons to safely and effectively operate in an environment of mechanical and visual-feedback delay, extreme environments such as space, the sea, and the battlefield will no longer be places where patients are surgically "underserved". As social, political, and economic barriers to routine telesurgery are overcome, telesurgery networks will connect isolated and deprived patients with expert subspecialty surgical care.

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