

An Experimental Feasibility Study on Robotic Endonasal Telesurgery

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BACKGROUND: Novel robots have recently been developed specifically for endonasal surgery. They can deliver several thin, tentacle-like surgical instruments through a single nostril. Among the many potential advantages of such a robotic system is the prospect of telesurgery over long distances.

OBJECTIVE: To describe a phantom pituitary tumor removal done by a surgeon in Nashville, Tennessee, controlling a robot located approximately 800 km away in Chapel Hill, North Carolina, the first remote telesurgery experiment involving tentacle-like concentric tube manipulators.

METHODS: A phantom pituitary tumor removal experiment was conducted twice, once locally and once remotely, with the robotic system. Robot commands and video were transmitted across the Internet. The latency of the system was evaluated quantitatively in both local and remote cases to determine the effect of the 800-km distance between the surgeon and robot.

RESULTS: We measured a control and video latency of < 100 milliseconds in the remote case. Qualitatively, the surgeon was able to carry out the experiment easily and observed no discernable difference between the remote and local cases.

CONCLUSION: Telesurgery over long distances is feasible with this robotic system. In the longer term, this may enable expert skull base surgeons to help many more patients by performing surgeries remotely over long distances.

KEY WORDS: Reaction time, Remote operations, Robotics, Skull base, Telerobotics

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The concept of remote telesurgery was a central motivation in the early development of surgical robots.¹ This led directly to the first commercial systems and to Operation Lindbergh in 2001,² a celebrated milestone in robotic telesurgery in which a surgeon in New York performed a robotic cholecystectomy on a patient in Strasbourg, France. Recent years have seen additional telesurgery demonstrations, including a laparoscopic cholecystectomy on pigs between Korea and Japan,³ a method for an atrial fibrillation ablation between Boston and Milan,⁴ and even a demonstration using a robot on the ocean floor by a surgeon on land.⁵ However, endonasal surgery has not yet been demonstrated in a telesurgical setting because traditional surgical robots⁶ are not well suited to transnasal surgery owing to large tool diameters

and the inability to coordinate the delivery of multiple tools through a nostril.

Lacking a suitable robot, prior studies on remote interaction in otolaryngology have focused on telementoring for preoperative planning and consultation over the Internet.^{7–9} Remote patient monitoring in otolaryngology⁸ and remote endoscope control in various surgical contexts^{10,11} have also been explored. Transmission of navigation information¹² has also been accomplished over long distances, and images (both preoperative computed tomography and intraoperative video), 3-dimensional models, a surgical plan, and even digitized locations of standard surgical instruments were transmitted in real time over the Internet during an endonasal procedure.¹³ However, remote control of surgical instruments themselves has not yet been accomplished. Fortunately, recent breakthroughs in robotics, notably the invention of concentric tube robots (a review on this

ABBREVIATION: IAT, interarrival time

technology is available elsewhere¹⁴), have inspired the development of a purpose-built teleoperated system for endonasal skull base surgery.¹⁵⁻¹⁷ Previously, the surgeon using these systems has always been located in the same room as the patient, not at a remote location. Thus, in this article, we use this system to explore for the first time the idea of remotely controlling surgical tools over long distances for endonasal skull base surgery, with tool motions and endoscopic video transmitted over the Internet.

The design of our endonasal robot has previously been described in the literature.^{15,18,19} Briefly, it functions by delivering several concentric tube manipulators (Figure 1) through a nostril. These manipulators are constructed from concentric, elastic tubes (made of Nitinol) that can be telescopically extended and axially rotated at their bases, in a manner conceptually similar to that of the guide wire of a catheter. In addition, like a guide wire, each tube is precurved; hence, the tubes elastically interact as they slide over one another. The result is a device that can both elongate and bend, and mechanics-based models are used to describe the curve of the manipulator as a function of tube base axial angles and telescopic extension distances.²⁰ Surgical instruments such as endoscopic cameras, grippers, curettes, and suction and irrigation can be delivered to the surgical site at the tips of these manipulators (Figure 2). We note that further hardware development will be needed before this system is ready for in vivo human use. We envision the system eventually having modular instrument attachments similar to the Intuitive Surgical da Vinci system, so that instruments can be exchanged during surgery (see the works by Burgner et al¹⁵ and Swaney et al¹⁸ for further discussion of the current prototype and the long-term vision for the robot hardware). Fortunately, because similar motors and components will be used in an eventual clinical system, we need not wait until the hardware is human ready before we perform many technical tests with the system. These include exploring the ability of surgeons to use it to resect tumors and the potential for remote teleoperation. Indeed, we have already completed preliminary experiments with this prototype in which experienced surgeons used it to remove anthropomorphic phantom pituitary tumors.^{16,21} Our goal here is to explore the feasibility of telesurgery with this prototype by performing



FIGURE 1. An active cannula gripper together with a da Vinci gripper.



FIGURE 2. Setup trial of the transnasal skull base surgery robot system in a human cadaver head and the endoscopic view of the pituitary gland.

a similar experiment with surgeon commands transmitted over the Internet to a remote location.

METHODS

Our experiment was conducted as illustrated in Figure 3, and the goal of this experiment was to examine whether distance and Internet transmission of surgeon’s commands would significantly affect the surgeon’s ability to resect pituitary tumors using the robot. The surgeon manipulated a master interface (Phantom Omni, Sensable, Inc) to control the concentric tube manipulators under endoscopic visualization. The surgeon’s motions were mapped to robot motions using a standard resolved-rates algorithm.¹⁵ The robot was placed locally (ie, in the same room as the surgeon) in 1 trial and remotely (approximately 800 km away) in the other using the same type of connection (1 GB/s) and the same framework described by Yu et al²² (The connection between the 2 universities was 10 GB/s, but the bottleneck is the 1-GB/s connection from each laboratory to the Internet backbone of the university). Thus, the only difference between the 2 cases is the presence of the Internet connection in the remote experiment, which introduces some latency. In each case, a phantom tumor was placed in the sella of an artificial skull according to procedures developed previously for local experiments of the same type.^{15-17,23,24} During the remote experiment, the surgeon was located at Vanderbilt University (Nashville, Tennessee), and the robot was located at the University of North Carolina at Chapel Hill (Chapel Hill, North Carolina). We used a computer to capture the endoscope video and to send this video to the surgeon using the free,

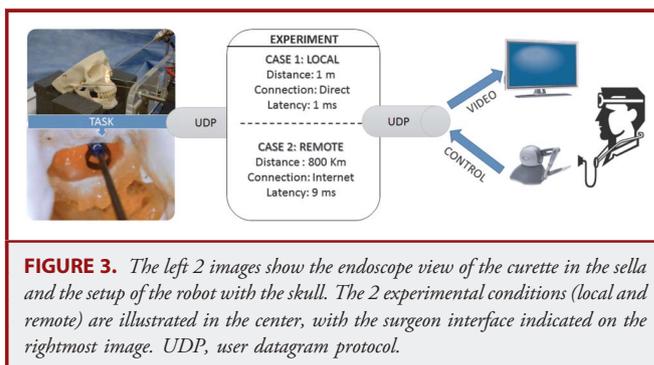


FIGURE 3. The left 2 images show the endoscope view of the curette in the sella and the setup of the robot with the skull. The 2 experimental conditions (local and remote) are illustrated in the center, with the surgeon interface indicated on the rightmost image. UDP, user datagram protocol.

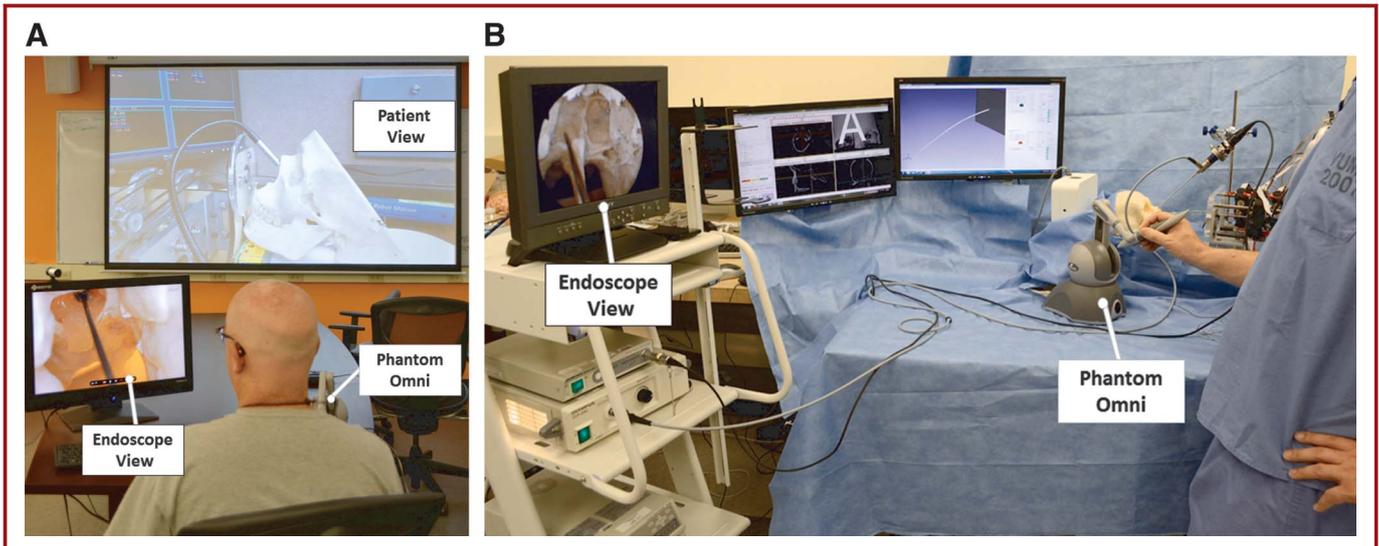


FIGURE 4. A, a surgeon in Nashville using a robot located in North Carolina to remove phantom pituitary tissue. B, experimental setup of the local experiment with both the robot and surgeon at Vanderbilt.

publicly available Skype software, which is designed for low-latency videoconferencing.²⁵

To explore the quality of the connection quantitatively, we used 2 well-established metrics: latency^{26,27} and interarrival time (IAT).²⁸ Latency is the time that 1 control packet takes to travel from where it originates to its destination, and its value depends directly on factors such as network congestion and the specifics of operating systems and routers that handle the packets during their transit. If latency becomes large, the robot will move sluggishly, and excessive latency will affect surgical performance.²⁹ IAT is defined as the time between the receipt of 2 consecutive packets at the surgeon-side computer, which can also vary as a result of network congestion. Large variations in IAT will reduce the smoothness of response of the robot to the surgeon's commanded motions.

RESULTS

The surgeon carried out each phantom tumor resection experiment in 20 minutes in both the local case (where the robot was in the same room as the surgeon) and the remote case (where the robot was located 800 km distant). Figures 4 and 5 provide illustrations of the experimental setup. During this 20-minute period, approximately 120 000 packets were transferred and analyzed to determine latency and IAT (Table). In Figure 6, a random sample of 500 packets of raw latency data is shown for both cases. Five minutes was selected simply because it is a convenient visualization of differences between local and remote experiment, and the data were sufficiently consistent that one 5-minute window looked visually much like any other. The Table summarizes all packets collected during the 20-minute experiment. Figure 7 shows a sample of the IAT data for the same time period illustrated in Figure 6. Note that the IAT is nominally 10 milliseconds in both cases because packets are transmitted at 10-millisecond intervals. As one would expect, the

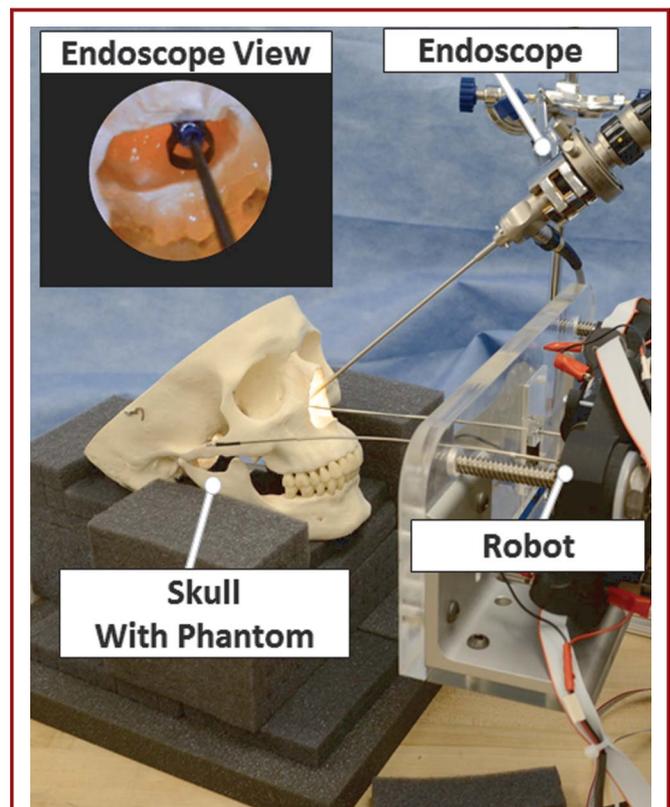


FIGURE 5. Setup trial of transnasal skull base surgery robot system with the endoscopic view of the phantom tumor and the Sella.

TABLE. Data for Both the Local and Remote Experiments

	Case 1: Local				Case 2: Remote			
	Average	Maximum	Minimum	SD	Average	Maximum	Minimum	SD
Latency, ms	1.1	4	1	0.66	10.37	22	9	2.77
Interarrival time, ms	10	18	1	2.51	10.17	50	>0	4.83

average IAT in both experiments was close to 10 milliseconds, with larger maximum and minimum values in the remote experiment as a result of Internet congestion.

Finally, the surgeon was asked to describe his perception of operating the remote system compared with operating the same system locally. He noted that he observed no discernable difference in system performance and had to keep reminding himself that the robot was hundreds of miles away from him because the experience for him was the same locally or remotely. He noted that he did not experience any difficulty with control smoothness or hand-eye coordination in either case.

DISCUSSION

When considering latency in surgery, the most important issue is whether the surgeon perceives the robot as lagging behind his or her hand motions during use. It is well established in the engineering literature that this dissociation between input and output motions starts at about 100 milliseconds^{29,30} and can become problematic at latencies greater than 300 milliseconds,³¹ at which point a latency control/manager³² must generally be introduced to assist the user. Operation Lindbergh² reported a control latency of approximately 40 milliseconds and found that this latency did not affect surgeon’s perception of the safety of the operation because all surgeons gave the system a perfect subjective score in “perception of the safety of the operation.”³³

We note that Operation Lindbergh used a dedicated telecommunications connection, which is useful for ensuring quality of

service but is challenging to set up and costly. Thus, it is desirable to use an Internet-based approach, although future hurdles exist in terms of ensuring the quality of service over the Internet. Still, we believe that because Internet networking protocols are improving all the time, it is reasonable to foresee a time in the not-too-distant future when Internet protocols are sufficiently reliable to enable Internet-based telesurgery. Indeed, by 2006, networking technology improvements enabled 6.5 milliseconds of control latency in a laparoscopic cholecystectomy between Korea and Japan.³ In our experiment, even in the presence of standard Internet traffic, the surgeon’s control signal had an average latency of 10.37 milliseconds, which is lower than the latency of Operation Lindbergh, which was sufficient for laparoscopic cholecystectomy. In our experiments, standard deviations (Table) illustrate that as one would expect, there is more variation in control signal latency and IAT in the remote case than in the local case (see also Figures 6 and 7 for illustration). However, as mentioned previously, these variations were sufficiently low that they did not affect surgeon perception of teleoperation.

With regard to the video transmission, Skype delivered a video latency with an average of 80 milliseconds, which represents better performance than both Operation Lindbergh and the Korea-Japan experiment³ mentioned previously, which reported latencies of 155 and 435.5 milliseconds, respectively. We note that in the future, before our system can be used with human subjects, it will require video transmission software that has been designed for remote surgery and rigorously tested. Our results indicate that

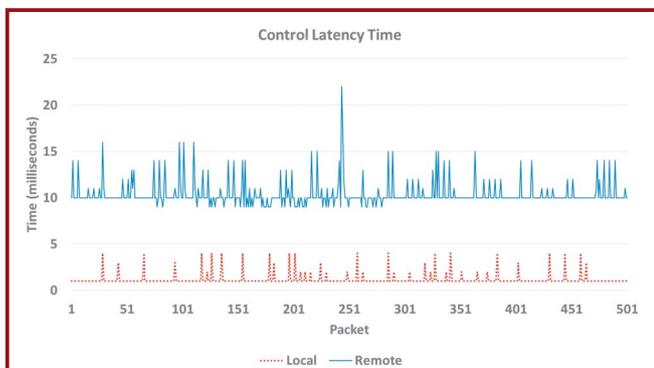


FIGURE 6. The latency in the surgeon’s control commands for both experiments.

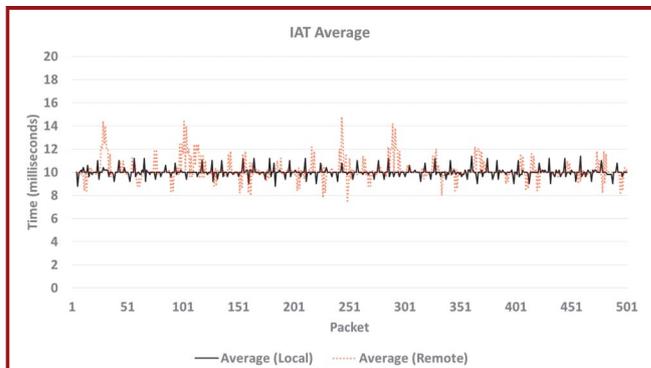


FIGURE 7. Sample of interarrival time (IAT) for the same time period shown in Figure 6. The moving average over 5 packets is shown.

a Skype-like program could achieve this goal, but we note that other video transmission architectures designed specifically for surgery such as the system by Klapan et al¹³ would be applicable to our system if needed.

In summary, our results indicate that extremely low latencies are possible over standard Internet connections with the use of off-the-shelf software. However, a dedicated connection would be recommended to control the delay. There are many next steps with our robotic system. First, we are currently designing modular tool interfaces similar to the da Vinci robot so that tools can be easily changed during surgery. We are also simultaneously addressing sterilizability concerns. The next step will be experiments to validate the system when interacting with perfused tissues, possibly in an animal model, and additional cadaver testing. It will take a few years to complete these tests, but once they are accomplished and we are able to perform our first live human case, it is useful to know that long-distance teleoperation will be straightforwardly feasible, as we have shown here.

CONCLUSION

We have described an initial feasibility study on telesurgery for endonasal skull base surgery. This was enabled by the recent development of the first robot specifically designed for endonasal surgery. Such a telesurgery system complements prior results in telementoring by providing a way for the remote surgeon to actively participate in the surgery for educational purposes or to bring the advantages of endonasal surgery to a wider range of patients. Our feasibility study showed that it is possible to achieve low latency and low IAT with this surgical robot, indicating that it is probably possible to achieve telesurgery with its use. This agreed with the qualitative feel of the surgeons who used the system, who noted that the remote experiment did not feel significantly different to them from the local experiment and that they were very confident that they could use such a robot to perform a real surgery. Thus, in summary, we demonstrated that critical components required for a telesurgery system for endonasal skull base surgery were effective, and we look forward to a future in which concentric tube robots are widely deployed in hospitals and used in endonasal skull base procedures in both a local and a remote context.

Disclosures

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COMMENT

The authors present a feasibility study on an imaginative paradigm in which a surgeon may perform endonasal robotic surgery from a remote location. With the need for specialty expertise rising faster than the supply of experts, such a paradigm would geographically expand the scale of influence of an individual specialized surgeon. Consequently, this feasibility demonstration is timely and visionary. In this technical demonstration, the authors show that a concentric tube robot can be operated remotely with manageable latencies. However, this static phantom model does not address the dynamic variables of reality (eg, bleeding, pulsations, tactile feedback). In a more dynamic surgical field, this degree of latency must be further scrutinized.

For a remote robotic paradigm to be realized, there are many important hurdles to be addressed beyond the technology described here. First and foremost is the safety of the patient and the perception thereof of the basic concept of a remote operator. Although technology may advance faster than public opinion, it is unclear how regulatory bodies may view safety under such a paradigm. Well-designed and publicized studies are required to show safety equivalence of a remote surgeon. Second, a tangible economic value proposition must be demonstrated to the host organization because the capital and operational expenses must be overcome by a reimbursement, which is not yet delineated in telesurgery. Finally, the widespread adoption of robotic remote surgery will have to compete with an emerging “destination” services model. Nevertheless, the first steps in the proof of principle are lauded in this article.

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