Influence of network latency and bandwidth on robot-assisted laparoscopic telesurgery: A pre-clinical experiment

Ye Wang[1], Qing Ai[1], Taoping Shi[2], Yu Gao[1], Bin Jiang[1], Wuyi Zhao[3], Chengjun Jiang[3], Guojun Liu[1], Lifeng Zhang[1], Huaikang Li[1], Fan Gao[1], Xin Ma[1], Hongzhao Li[1], Xu Zhang[1]

[1]Department of Urology, Chinese People's Liberation Army General Hospital, Beijing 100853, China;
[2]Department of Urology, Hainan Hospital of Chinese People's Liberation Army General Hospital, Beijing 100853, China;
[3]Shenzhen Edge Medical Co., Ltd, Shenzhen, Guangdong 518116, China.

Abstract

Background: Telesurgery has the potential to overcome spatial limitations for surgeons, which depends on surgical robot and the quality of network communication. However, the influence of network latency and bandwidth on telesurgery is not well understood.

Methods: A telesurgery system capable of dynamically adjusting image compression ratios in response to bandwidth changes was established between Beijing and Sanya (Hainan province), covering a distance of 3000 km. In total, 108 animal operations, including 12 surgical procedures, were performed. Total latency ranging from 170 ms to 320 ms and bandwidth from 15–20 Mbps to less than 1 Mbps were explored using designed surgical tasks and hemostasis models for renal vein and internal iliac artery rupture bleeding. Network latency, jitter, frame loss, and bit rate code were systemically measured during these operations. National Aeronautics and Space Administration Task Load Index (NASA-TLX) and a self-designed scale measured the workload and subjective perception of surgeons.

Results: All 108 animal telesurgeries, conducted from January 2023 to June 2023, were performed effectively over a total duration of 3866 min. The operations were completed with latency up to 320 ms and bandwidths as low as 1–5 Mbps. Hemostasis for vein and artery rupture bleeding models was effectively achieved under these low bandwidth conditions. The NASA-TLX results indicated that latency significantly impacted surgical performance more than bandwidth and image clarity reductions.

Conclusions: This telesurgery system demonstrated safety and reliability. A total of 320 ms latency is acceptable for telesurgery operations. Reducing image clarity can effectively mitigate the potential latency increase caused by decreased bandwidth, offering a new method to reduce the impact of latency on telesurgery.

Keywords: Telesurgery; Latency; Bandwidth; Image clarity; Surgical robot

Introduction

Telesurgery refers to surgical procedures performed using telecommunication technology, with the potential to transform the global healthcare landscape by improving accessibility and quality, especially in resource-limited settings and on the front lines of battlefields.[1,2] This technology combines modern communication and surgical robots, allowing surgeons to perform procedures from remote or safe locations while ensuring high-quality surgical results and patient safety.[3–5] Telesurgery has been widely explored in various medical fields, including urology,[6] neurology,[7] general surgery,[8,9] cardiovascular,[10] and orthopedics.[11] It enhances access to surgical services, reduces travel time and expenses, and provides more professional care. Although telesurgery requires a high-level of skill and expertise, its success depends on close collaboration and careful planning between the surgeon and the medical team. Additionally, a high-quality network is essential to ensure smooth telesurgery procedures,[12,13] with latency and bandwidth being key factors affecting network quality. However, the impact of these factors on telesurgery is not yet fully understood.

Thus, in this study, we investigated the influence of network latency and bandwidth on the safety of telesurgery

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Ye Wang and Qing Ai contributed equally to this work.

Correspondence to: Xu Zhang, Department of Urology, The Third Center of Chinese People's Liberation Army General Hospital, Beijing 100853, China
E-Mail: xzhang@foxmail.com;
Hongzhao Li, Department of Urology, The Third Center of Chinese People's Liberation Army General Hospital, Beijing 100853, China
E-Mail: urolancet@126.com;
Xin Ma, Department of Urology, The Third Center of Chinese People's Liberation Army General Hospital, Beijing 100853, China
E-Mail: mxin301@126.com

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and the task load of surgeons. This research contributes to the advancement of clinical trials in telesurgery.

Methods

Telesurgery system structure

The telesurgery system mainly consisted of three components: Surgical robot subsystem, telecommunications subsystem, and teleconference subsystem. The surgical robot subsystem included a surgeon console and a patient cart, with the surgeon console located at the Chinese People's Liberation Army (PLA) General Hospital in Beijing and the patient cart located at Hainan Hospital of the Chinese PLA General Hospital in Sanya (Hainan province), nearly 3000 km apart. The telecommunications subsystem comprised the router and communication lines provided by the network operator. The teleconference subsystem (XYlink, China) facilitated communication between the lead surgeon and assistants, transmitting the views and voices of the lead surgeon and the operating room [Figure 1].

Network connections

In this research, an optical transport network (OTN) dedicated line (China Telecom Co., Ltd, Beijing, China) with a maximum bandwidth of 60 Mbps was used for the communication of the robot subsystem. A standard 5G wireless network was used for the teleconference subsystem.

Surgical robot subsystem

The robot subsystem used in the telesurgery system was the MP1000 surgical robotic system (Shenzhen Edge Medical Co., Ltd, Shenzhen, China), which includes three main components: The surgeon's console, the patient-side cart, and the 3-Dimensional High Definition (3DHD) vision system. The MP1000 features four robotic arms that facilitate switching between arms during complex procedures. Each robotic arm and instrument have 12 degrees of freedom, providing natural dexterity and a broad range of motion for port placement, docking, and surgical manipulation. The vision system delivers high-definition images with minimal latency. The laparoscopic signal was compressed and decompressed using a customized encoder and decoder that employs H.265, a video compression algorithm that uses motion compensation prediction and larger macroblocks to achieve higher efficiency.[14]

Animals

Healthy pigs were utilized in this study. They underwent sedation with an intramuscular injection of ketamine (10 mg/kg) and xylazine (2 mg/kg), with muscle relaxation induced by 3 mg of vecuronium. Following the experiment, cardiac arrest was induced under deep anesthesia. All animal experiments were conducted in accordance with the Guide for the Care and Use of Laboratory Animals and were approved by the Bioethics Committee of the Chinese PLA General Hospital (No. LS-QX-2023-006). The experiments adhered to the relevant guidelines

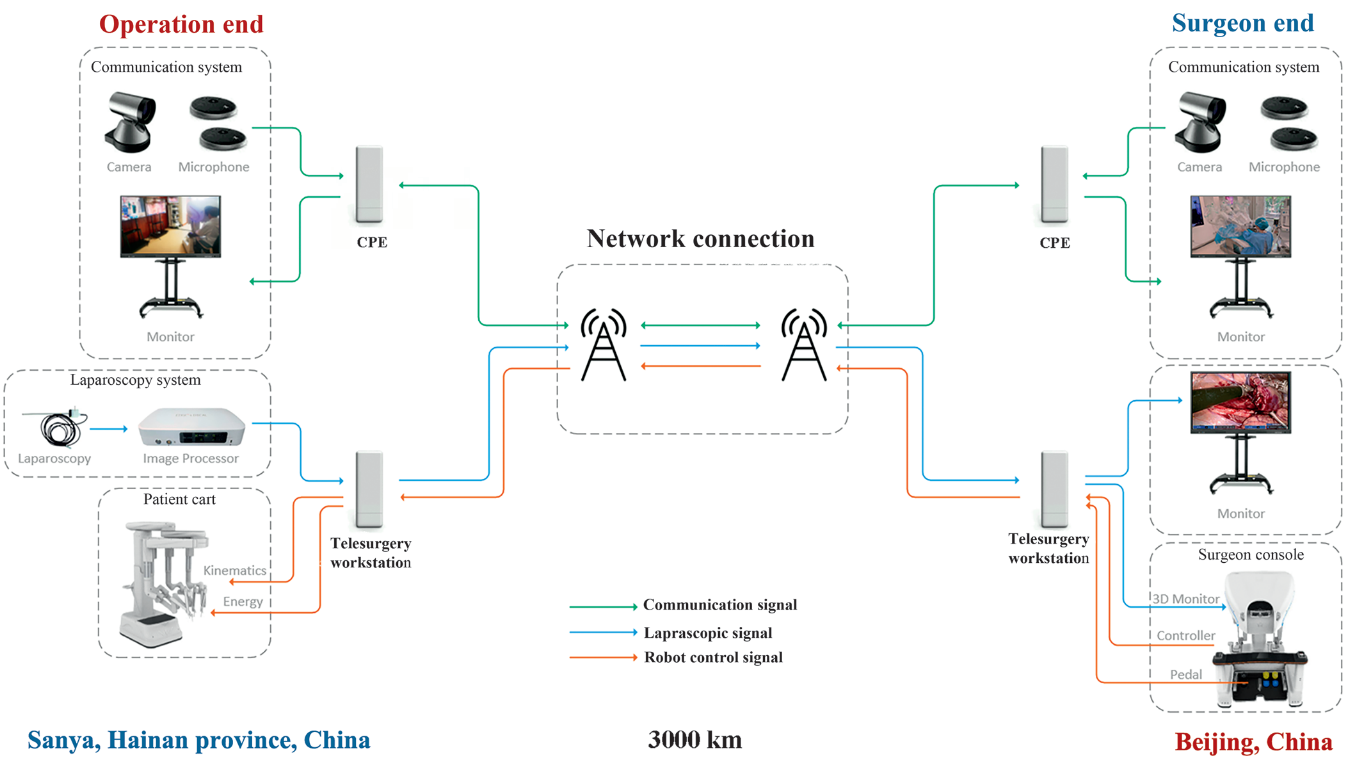

Figure 1: Structure of the telesurgery system. The telesurgery system comprises three subsystems: the surgical robot subsystem, telecommunications subsystem, and teleconference subsystem. In the surgical robot subsystem, the surgeon's console was located in Beijing, and the patient-cart end was located in Sanya, Hainan province. The dedicated Internet network line spanned approximately 3000 km, crossing the Qiongzhou Strait. CPE: Customer premise equipment.

and regulations of the Chinese PLA General Hospital. Additionally, this research followed the Animal Research: Reporting *In Vivo* Experiments (ARRIVE) Guidelines.

Latency and bandwidth settings

To explore the impact of weak network connections, bandwidths ranging from 15–20 Mbps, 10–15 Mbps, 1–5 Mbps, and 700 kbps were utilized for testing. The natural bandwidth was 15–20 Mbps. By employing advanced video compression technology, only the image quality and bit rate were adjusted following the bandwidths switch, whereas network parameters such as communication latency remained in natural conditions. The image quality degradation for each bandwidth and its impact on the surgical procedure were analyzed. Surgeries were conducted with varying total latencies from 170 ms to 320 ms to assess the impact of latency. Network latency was controlled through the establishment of a video cache. Parameters including jitter, frame loss number, bit rate, and network round-trip latency were evaluated.

Operation performance and vascular rupture model

All the operations were conducted following standard protocols. Recognizing the significance of hemostasis in surgical procedures, models simulating renal vein rupture and internal iliac artery bleeding were devised. A single-blind method was employed in the hemostasis test with the hemostatic operator performing the procedure after another surgeon had completed the bleeding model.

Task load under different latencies and bandwidths

To assess surgeons' task load across various latency and bandwidth scenarios, six surgeons were tasked with completing four surgical procedures: (1) opening and closing of instruments, movement, and switching between robotic arms; (2) fat removal and hemostasis; (3) repair of bladder or small intestine rupture; and (4) partial nephrectomy. Simultaneously, hemostasis was performed under different bandwidths ranging from natural 15–20 Mbps to 10–15 Mbps, 1–5 Mbps, and 700 kbps. The Improved National Aeronautics and Space Administration Task Load Index (NASA-TLX) for telesurgery was employed to gauge surgeons' task load [Supplementary File 1, http://links.lww.com/CM9/C107].

The NASA-TLX measures an individual's experience of situational demands at work, including mental demand, physical demand, time pressure, performance level, effort, and frustration level.[15] Overall workload scores were calculated by summing scores from these six items, ranging from score 0 (very low) to 20 (very high).

All six surgeons, each possessing certified robotic-assisted surgery proctor status or equivalent experience, participated in the experiment. Other operations were conducted under the natural conditions of the telesurgery system.

Subjective perception of telesurgery

The Telesurgery Subjective Perception Assessment Scale (TSPAS) was designed to evaluate the subjective perception of telesurgery in this study [Supplementary File 2, http://links.lww.com/CM9/C107]. TSPAS comprises three dimensions: latency stability index, surgical operation index, and endoscopic quality index. Ratings were established on a five-level scale: completely impossible (score 1) to possible (score 5), and the higher score reflects the better subjective feeling.

Statistical analysis

The Student's *t*-test was employed to analyze the data, with statistical significance set at $P < 0.05$. All analyses were conducted using SAS version 9.4 (SAS Institute Inc., Cary, USA). Visualization of telesurgery system monitoring data was performed using GraphPad Prism 8.0 (GraphPad Software, California, USA).

Results

Procedures and outcomes of telesurgeries

A total of 12 surgical procedures and 108 operations were performed in this study, including partial nephrectomy (n = 26), nephrectomy (n = 12), nephroureterectomy (n = 2), ureter-bladder replantation (n = 14), ureteral anastomosis (n = 12), bladder rupture repair (n = 12), prostatectomy (n = 2), pelvic lymph node dissection (n = 4), ruptured inferior vena cava repair (n = 2), small intestine anastomosis (n = 16), uterine rupture repair (n = 2), and oophorectomy (n = 4). All operations were safely completed using our telesurgery system without the need for local surgery. Only two breakdowns (1.85%) of the telesurgery system were observed during the research, attributed to significant packet dropout, but were promptly repaired. The total operation test time in this research amounted to 3866 min. Additionally, 93 operations were conducted under natural conditions without intervention in network latency and bandwidth to assess the stability of the telesurgery system simultaneously. As multiple operations were performed on the same animal according to the animal welfare principles, further follow-up was not carried out.

Basic test results of the telesurgery system

We conducted testing on basic communication parameters within the telesurgery framework. Total latency was defined as the duration between hand manipulation and the appearance of the endoscope image on the surgeon's control monitor, encompassing patient cart-control signal processing latency, network round-trip latency, and video signal compression and decompression latency, which was the sum of robot system latency and round-trip network latency in other word. Data from 93 operations conducted under natural conditions of telesurgery were recorded. The median of the mean round-trip network latency was 49.53 ms (interquartile range [IQR] = 49.52–50.00 ms) [Figure 2A].

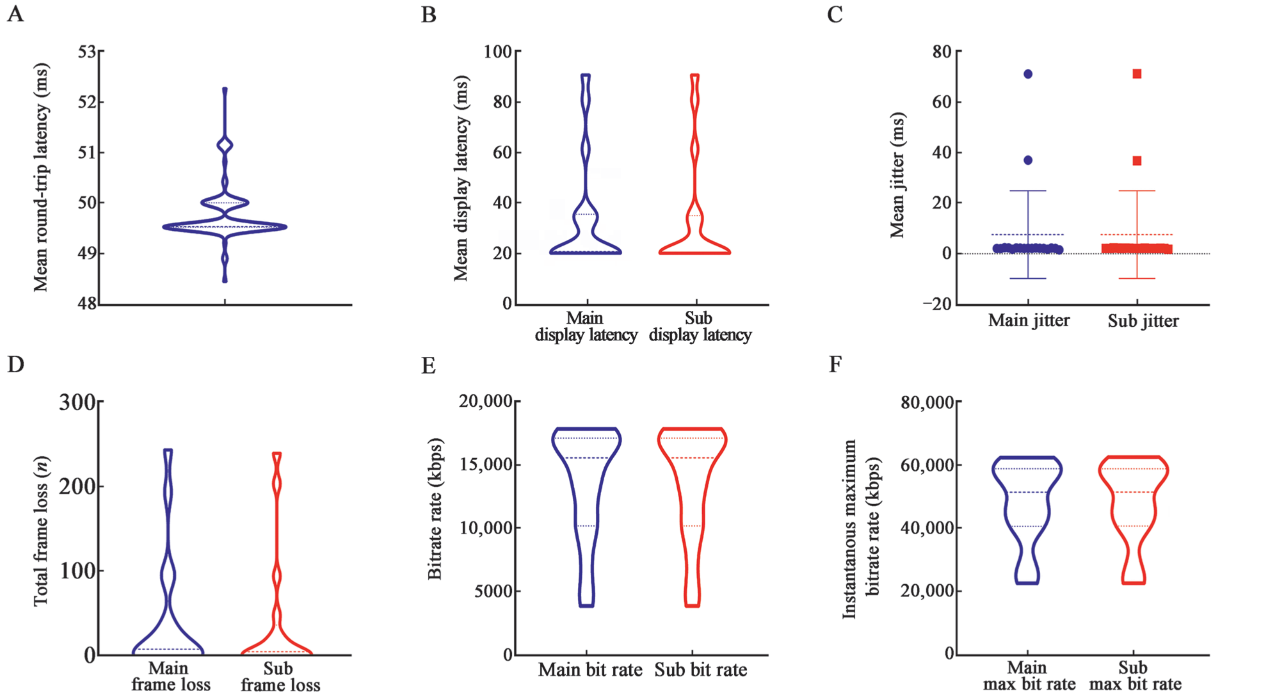

Figure 2: Basic communication test results of the telesurgery system. (A) The median of the mean round-trip network communication latency was 49.53 ms (IQR = 49.52–50.00 ms). (B) The median of the mean latency of the mainboard and subboard video package was 20.61 ms (IQR = 20.03–35.30 ms) and 20.17 ms (IQR = 20.01–34.76 ms). (C) The median of the mean jitter of the mainboard and subboard was 2.146 ms (IQR = 2.085–2.280 ms) and 2.097 ms (IQR = 2.061–2.228 ms), respectively. (D) Frame loss of mainboard and subboard package. The frame loss was very low or not observed. (E) The median bit rate of the mainboard and subboard were 15,544 kbps (IQR = 10,164–17,108 kbps) and 15,545 kbps (IQR = 10,165–17,106 kbps), respectively. (F) The instantaneous maximum bit rate of the mainboard and subboard were 51,453 kbps (IQR = 40,584–58,965 kbps) and 51,509 kbps (IQR = 40,695–58,935 kbps), respectively. IQR: Interquartile range.

The median of the mean display latency of the mainboard and subboard video package was 20.61 ms (IQR = 20.03–35.30 ms) and 20.17 ms (IQR = 20.01–34.76 ms), respectively [Figure 2B], whereas the median of mean jitter of the mainboard and subboard was 2.146 ms (IQR = 2.085–2.280 ms) and 2.097 ms (IQR = 2.061–2.228 ms), respectively [Figure 2C]. Frame loss was nearly negligible in many operations, indicating the stability of our telesurgery system based on the OTN dedicated line. However, some instances of frame loss were observed, although they had no significant impact on the operation and were deemed acceptable [Figure 2D]. Additionally, the median bit rate and instantaneous maximum bit rate for the mainboard and subboard were 15,544 kbps (IQR = 10,164–17,108 kbps) and 15,545 kbps (IQR = 10,165–17,106 kbps) and 51,453 kbps (IQR = 40,584–58,965 kbps) and 51,509 kbps (IQR = 40,695–58,935 kbps), respectively [Figure 2E, F]. Real-time round-trip network latency for all 93 operations under natural conditions was recorded [Supplementary Figure 1, http://links.lww.com/CM9/C107]. In this telesurgery system, the total latency averaged about 170 ms under natural conditions.

Evaluation of the task load under different latencies and bandwidths

First, we compared the impact of local surgery *vs*. telesurgery on surgeons' task load using the NASA-TLX by performing designated tasks.[15] The experiment's latency was set at 170 ms, 270 ms, and 320 ms. All designed operation tasks under different latencies were finished safely, including the partial nephrectomy [Supplementary Video 1, http://links.lww.com/CM9/C108]. Additionally, NASA-TLX was analyzed under different latencies. The index results revealed that increased latency did not significantly affect mental and physical demands, performance level, or frustration. However, there was a significant increase in time demand and effort level [Table 1].

In our telesurgery system, image clarity can be adjusted in response to network bandwidth [Figure 3]. The designated tasks were also tested under different bandwidths,

Table 1: NASA-TLX of designed tasks on different total latencies.

	Latencies		
NASA-TLX subscale	170 ms	270 ms	320 ms
Mental demand increase	2.33 ± 1.21	1.50 ± 0.85 (P = 0.20, t = 1.39)	2.66 ± 1.86 (P = 0.72, t= −0.37)
Physical demand increase	1.16 ± 0.75	1.50 ± 0.55 (P = 0.40, t = −0.88)	1.83 ± 0.98 (P = 0.22, t = −1.32)
Time demand increase	1.83 ± 1.16	1.66 ± 0.85 (P = 0.78, t=0.29)	3.17 ± 0.75 (P = 0.04, t = −2.35)
Performance level decrease	18.1 ± 1.47	18.30 ± 1.37 (P = 0.84, t = −0.20)	18.00 ± 1.26 (P = 0.84, t = 0.21)
Level of effort increase	1.33 ± 1.36	2.00 ± 1.36 (P = 0.84, t = −0.21)	3.33 ± 0.82 (P = 0.02, t = −2.18)
Frustration increase	1.33 ± 1.36	1.50 ± 1.38 (P = 0.84, t = −0.21)	1.50 ± 1.22 (P = 0.83, t = −0.22)

Values were shown as mean ± standard deviation, statistics were analyzed compared with the 170-ms latency. NASA-TLX: Improved National Aeronautics and Space Administration Task Load Index.

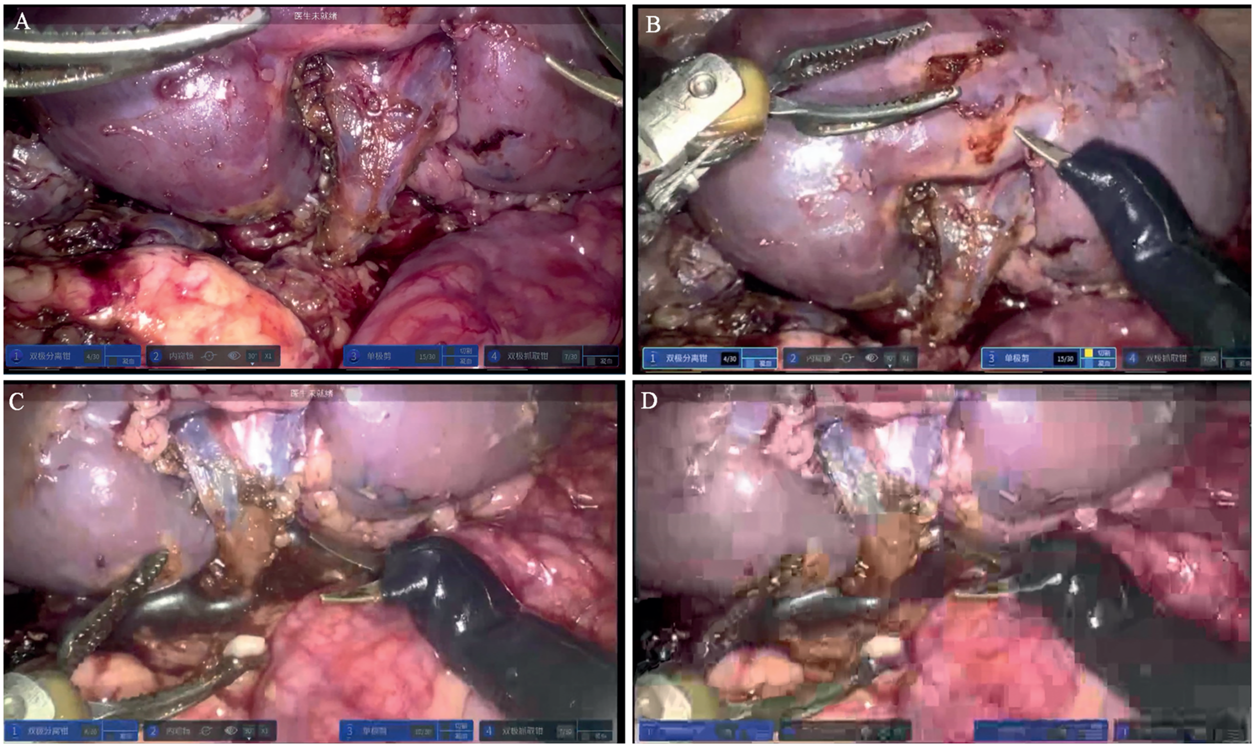

Figure 3: Laparoscopic images under different bandwidths in partial nephrectomy. (A) 15–20 Mbps, very clear; (B) 10–15 Mbps, clear; (C) 1–5 Mbps, unclear; and (D) less than 1 Mbps, blurry.

including partial nephrectomy [Supplementary Video 2, http://links.lww.com/CM9/C109]. Results indicated that subscales such as mental, physical, frustration, and performance level were minimally affected by bandwidth reduction, except for time demand under 1–5 Mbps [Table 2]. Furthermore, image clarity under the bandwidth of 700 kbps made it challenging for surgeons to identify tissue structures, rendering task load and operations cannot be tested.

The task load assessment of telesurgery under varying latency and bandwidth highlighted that latency may have a greater impact on telesurgery safety. In our telesurgery system, the video compression method effectively responded to narrow communication bandwidth, reducing image clarity and mitigating latency increase.

Table 2: NASA-TLX of designed tasks on different bandwidths.

	Bandwidths		
NASA-TLX subscale	15–20 Mbps	10–15 Mbps	1–5 Mbps
Mental demand increase	2.33 ± 1.21	4.00 ± 1.26 (P = 0.04, t = –2.33)	3.33 ± 1.63 (P = 0.25, t = –1.20)
Physical demand increase	1.17 ± 0.75	2.16 ± 0.75 (P = 0.04, t = –2.30)	1.67 ± 0.81 (P = 0.30, t = –1.10)
Time demand increase	1.83 ± 1.16	2.66 ± 0.81 (P = 0.18, t = –1.43)	4.67 ± 1.63 (P = 0.006, t = –3.46)
Performance level decrease	18.17 ± 1.47	17.10 ± 1.16 (P = 0.22, t = 1.30)	17.00 ± 1.41 (P = 0.19, t = 1.40)
Level of effort increase	1.83 ± 1.47	3.16 ± 1.32 (P = 0.13, t = –1.65)	3.17 ± 1.60 (P = 0.16, t = –1.50)
Frustration increase	1.33 ± 1.36	2.00 ± 0.89 (P = 0.34, t = –1.00)	1.50 ± 1.37 (P = 0.84, t = –0.21)

Values were shown as mean ± standard deviation, statistics were analyzed compared with the 15–20-Mbps bandwidth. NASA-TLX: Improved National Aeronautics and Space Administration Task Load Index.

Hemostasis is a critical surgical procedure. Renal vein rupture and iliac artery rupture bleeding models were designed to explore the hemostatic effects of the telesurgery system under different bandwidths. A single-blind experiment of hemostasis was conducted. The results from the renal vein bleeding model indicated that the time demand and effort level scores increased significantly at bandwidth of 1–5 Mbps [Supplementary Table 1, http://links.lww.com/CM9/C107 and Supplementary Video 3, http://links.lww.com/CM9/C110]. In the arterial bleeding model, the subscale scores did not show significant increases, except for the effect level [Supplementary Table 2, http://links.lww.com/CM9/C107 and Supplementary Video 4, http://links.lww.com/CM9/C111].

Subjective perception of the telesurgery on partial nephrectomy

To explore the subjective perceptions of surgeons, TSPAS was utilized to evaluate the primary performance aspects of the telesurgery system during partial nephrectomy. Six surgeons with experience in robotic surgery participated in this study. The average time for partial resection and suturing of the kidney was 25.0 ± 4.5 min. TSPAS results indicated that the latency stability index, surgical procedures index, and endoscopic image quality index all scored above 4, demonstrating the acceptable performance of the telesurgery system [Figure 4 and Supplementary Table 3, http://links.lww.com/CM9/C107].

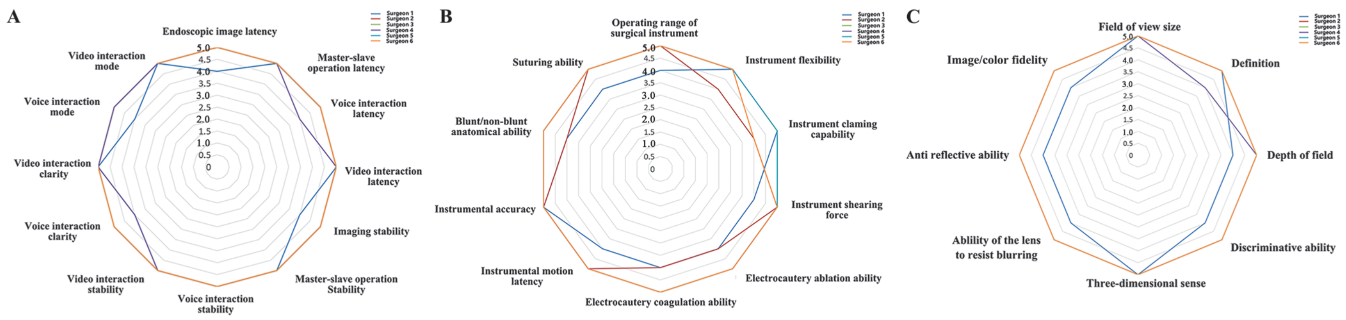

Figure 4: TSPAS results. (A) Latency stability index; (B) Surgical procedures index; and (C) Endoscopic image quality index. TSPAS: Telesurgery Subjective Perception Assessment Scale.

Discussion

Telesurgery has been successfully performed since 2001,[8] and over the past 23 years, surgeons and engineers have worked tirelessly to advance its development. Thus, improving the safety and stability of telesurgery as a medical procedure remains a constant goal.[16,17] Both dedicated lines and 5G wireless networks can be used for telesurgery communication. Due to its high stability, the OTN dedicated line was used in this research.

Latency in telesurgery primarily affects its safety, with lower latency being preferable. However, network conditions can experience sudden temporary increases in latency. In this research, we established a telesurgery system between Beijing and Sanya to examine the influence of latency and bandwidth on surgical safety. We used the NASA-TLX to analyze the task load on surgeons using the telesurgery system. Six senior surgeons with extensive experience in robotic surgery performed four surgical tasks. The results showed that surgical operation could be completed with a higher task load for surgeons at a latency of 320 ms. At this latency, surgeons reported a noticeable impact on the speed of procedures, and the NASA-TLX scores indicated a significant increase in task load, suggesting a reduction in telesurgery safety. Therefore, we did not explore higher latencies in this research due to the implications for human surgery. A total latency of 320 ms was considered the upper acceptable limit for telesurgery. Given the stability of the dedicated line, latency is mainly influenced by distance due to the speed limitation of light. We propose that there is an upper distance limit for telesurgery, which can be calculated based on the acceptable latency of 320 ms.

The telesurgery system used in this study employed an image compression strategy that could be adjusted according to changes in bandwidth to mitigate latency issues caused by a narrow bandwidth in weak network conditions. Multiple bandwidths settings were tested. We observed that reducing bandwidth led to decreased image clarity, which in turn helped to reduce latency increase. We further explored the task load on surgeons under varying bandwidth conditions. The results indicated that bandwidth narrowing and decreased image clarity had a smaller impact on surgeons than increased latency. This suggests that reducing image clarity can be an effective strategy to cope with latency issues caused by bandwidth narrowing, thereby improving the safety of telesurgical procedures.

Hemostasis is an important surgical procedure.[18] To further investigate the effects of bandwidth narrowing along with image clarity decreases on telesurgery, we designed renal vein and internal iliac artery rupture bleeding models along with the designed tasks and used the NASA-TLX index to evaluate the changes in task load under different bandwidth conditions. A single-blind method was adopted in this study to exclude pre-cognition of the rupture injury site by modelers. All bleeding models were effectively hemostatic, and no significant increase was observed in the task load for the arterial bleeding models. However, surgeons' task load increased in the renal vein bleeding models. The videos showed that the venous bleeding models exhibited localized bleeding due to intraperitoneal pressure, which obscured the bleeding point, especially when image clarity decreased. This likely contributed to the increased hemostatic time and physical exertion. By contrast, arterial bleeding displayed a spraying pattern, which allowed surgeons to quickly determine the approximate location of the bleeding based on the direction of the blood spraying, allowing for rapid clamp hemostasis, and creating opportunities for further repair.

In this research, frame loss was observed even though the dedicated line used for telesurgery was stable. However, due to the very low number of frame loss, the surgeons did not perceive obvious impact.

In conclusion, this study has revealed that increases in latency have a greater impact on the safety of telesurgery operations than bandwidth narrowing and the associated decrease in image clarity. This requires higher technical skills from surgeons. Additionally, this study proposes a new strategy for mitigating latency caused by bandwidth narrowing by appropriately decreasing image clarity, thereby further improving the safety of telesurgery.

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Conflicts of interest

None.

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