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Verification of delay time and image compression thresholds for telesurgery

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Abstract

Introduction: Telerobotic surgery relies on communication lines, causing delays, and video information requires pre-transmission compression. Such delays and video degradation will continue to be unavoidable making communication conditions verification essential. Understanding the network specification values required for telerobotic surgery entails determining acceptable levels of delay and degradation due to the video compression and restoration processes during surgery.

Methods: The hinotori™ surgical robot from Medicaroid was used. Eight surgeons, skilled in robotic surgery, performed gastrectomy or rectal resection on pigs. Image compression (bitrate: 120, 60, 30, 20, 10 Mbps) was random, changing encoder settings during surgery, and delay times (30, 50, 100, 150 milliseconds) were pseudo-randomly inserted, changing emulator settings. Acceptable video levels were evaluated. Subjective evaluations by surgeons and evaluators regarding image degradation and operability, and objective evaluations of image degradation and operability were given five-point ratings.

Results: Regarding delay time, 30 and 50 millisecond periods garnered average ratings of 3.6 and 4.0, respectively, signifying that surgery was feasible. However, at 100 and 150 millisecond, average ratings were 2.9 and 2.3, respectively, indicating surgery was not feasible for the most part in these cases. The average rating for image compression was 4.0 or higher for bitrates of 20, 30, 60, and 120 Mbps, suggesting that surgery is possible even at bitrates as low as 10 Mbps, with an average rating of 4.0.

Conclusion: In remote robotic surgery using the hinotori™, image compression and delay time are largely acceptable, so surgery can be safely performed.

KEYWORDS

delay time, image compression, telesurgery

1 | INTRODUCTION

Surgical robots are being developed to overcome the shortcomings of conventional endoscopic surgery. They feature advanced technologies such as anti-shake, multi-joint function, and 3D stereoscopic viewing. However, their superiority in terms of curative properties and long-term results is still unclear. The functional expansion of surgical robots continues unabated, and attractive new technologies such as navigation systems that apply affinity with digital functions, cognitive functions with artificial intelligence, orientation functions, tactile functions, educational functions with dual console and annotation, remote surgery, and so forth, are being installed one after another.[1,2]

In recent years, there have been growing expectations for the role of robotics not only as a means of performing surgery, but also as a tool to bring new added value to society. At this moment in time, mobility has become restricted due to widespread novel coronavirus infection (COVID 19), the inherent remote capabilities of telesurgery using surgical-assist robots is attracting attention.[3]

High expectations for telerobotic success are entirely reasonable given the development of high-speed, large-capacity communication technology in addition to the development of surgical support robots. As a result, an environment in which surgery can actually be performed remotely has become technically feasible. We conducted a remote surgery experiment using commercial lines between hospitals 150 km apart in February 2021 as a preliminary study. By providing sufficient communication bandwidth to match the characteristics of the robot and sufficient information processing technology to compress and restore information, we found that the communication delay was negligible and the delay time for the entire system was less than 100 milliseconds, which is considered sufficient for normal operation.[4] In a remote environment, there are issues of delay and image quality degradation caused by data compression and restoration during transmission of video and operation information. In order for telesurgery to be widely used, it is necessary to verify to what extent the delay and degradation of image quality are acceptable.

The purpose of this study is to evaluate the acceptable level of delay and image degradation caused by image compression and restoration during surgery using hinotori™, a robot-assisted surgical system developed recently in Japan by Medicaroid,[5] on a living body in order to know what actually are the network specifications required for telesurgery.

2 | MATERIALS AND METHODS

2.1 | Communication environment

A surgeon's cockpit (SC), operation unit (OU), and vision unit (VU) were installed in the same room (Figure 1). To simulate remote-operative conditions, the SC and VU were connected with an encoder/decoder and an emulator as intermediaries. The encoder/decoder inserted image degradation, and the emulator inserted delay time (Figure 2).

The delay time conditions were 30, 50, 100, and 150 milliseconds. For image compression, bit rates of 120, 60, 30, 20, and 10 Mbps were set.

2.2 | Operation robot

The surgical robot was the hinotori™, developed by Medicaroid. The hinotori™ consists of three units: an OU, a SC, and a VU. The SC was operated with a hand controller while viewing a close-type 3D monitor.

2.3 | Tasks

Eight surgeons, each of whom is a robotic surgery expert with certified robotic-assisted surgery proctor status or has the equivalent experience, were divided into four groups to perform the gastrectomy and rectal resection. There were no conflicts of interest for any of the subjects. A 10-minute practice period was provided beforehand, followed by the evaluation task. This 10-minute period was used to confirm how to operate the hinotori™ and to get a feel for its operation, including grasping tissue and cutting away areas that were not affected by the evaluation task. Subjects were tasked with a change in delay time and image compression 1 minute for each setting, followed by a 1 minute break before moving on to the next setting. During the task, they were asked to perform procedures such as mesenteric processing and perivascular dissection. The subjects performed with the SC covered by a partition screen so that they could not see which setting was being used at any given interval.

2.4 | Animals

Healthy pigs weighing 43.5 kg were used. They were sedated with an intramuscular injection of ketamine 10 mg/kg + xylazine 2 mg/kg and muscle relaxation was performed with 3 mg of vecuronium. After completion of

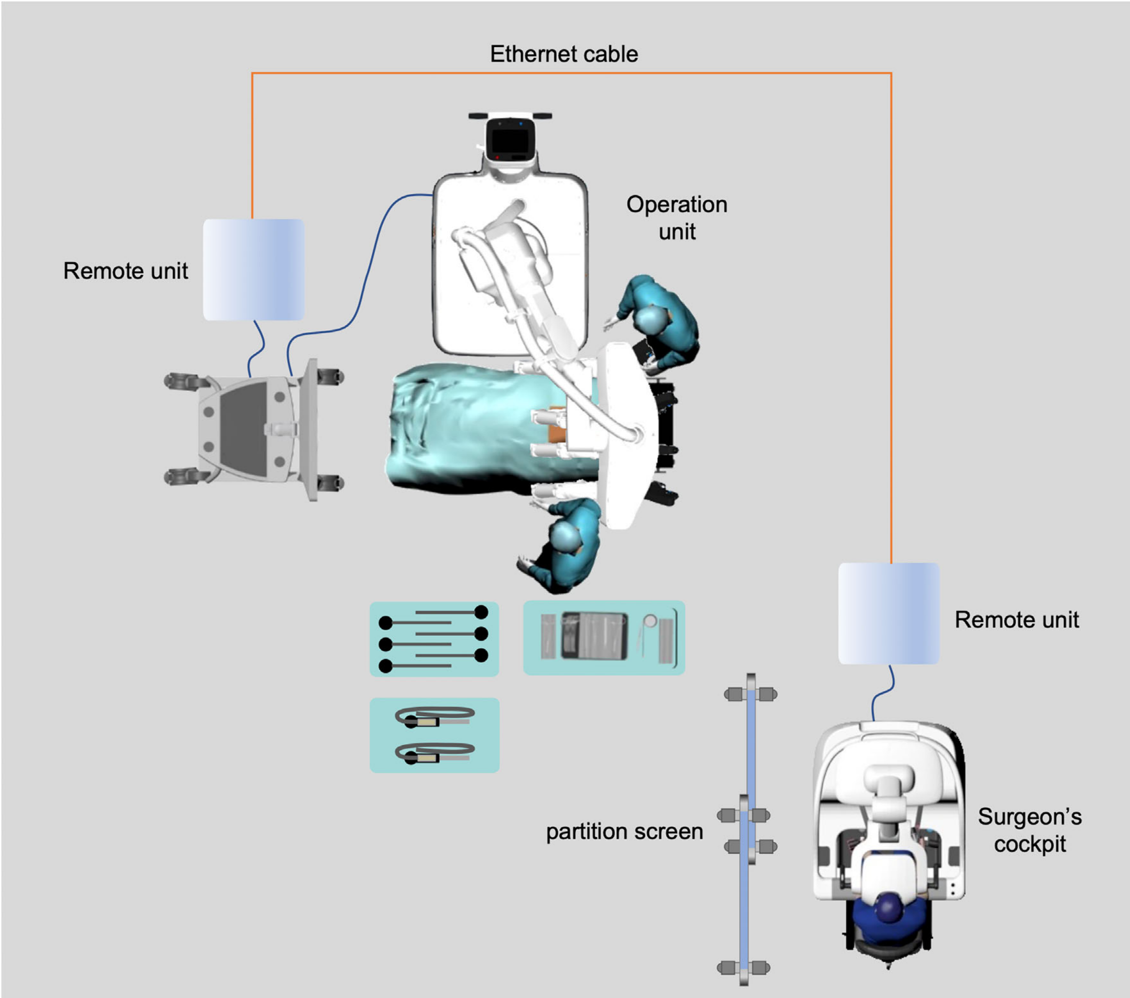


FIGURE 1 The surgeon's cockpit (SC), operations unit (OU), and vision unit (VU) were installed in the same room. The SC was covered by a partition screen.

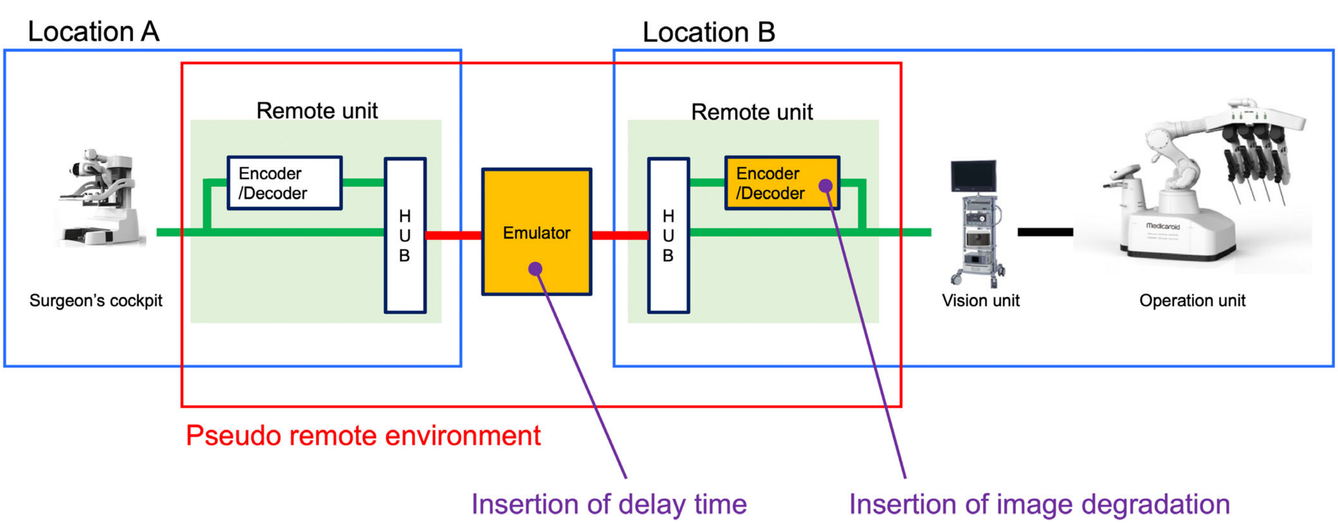


FIGURE 2 Simulated telesurgery conditions were used. Image degradation was inserted by the encoder/decoder, and delay time was inserted by the emulator.

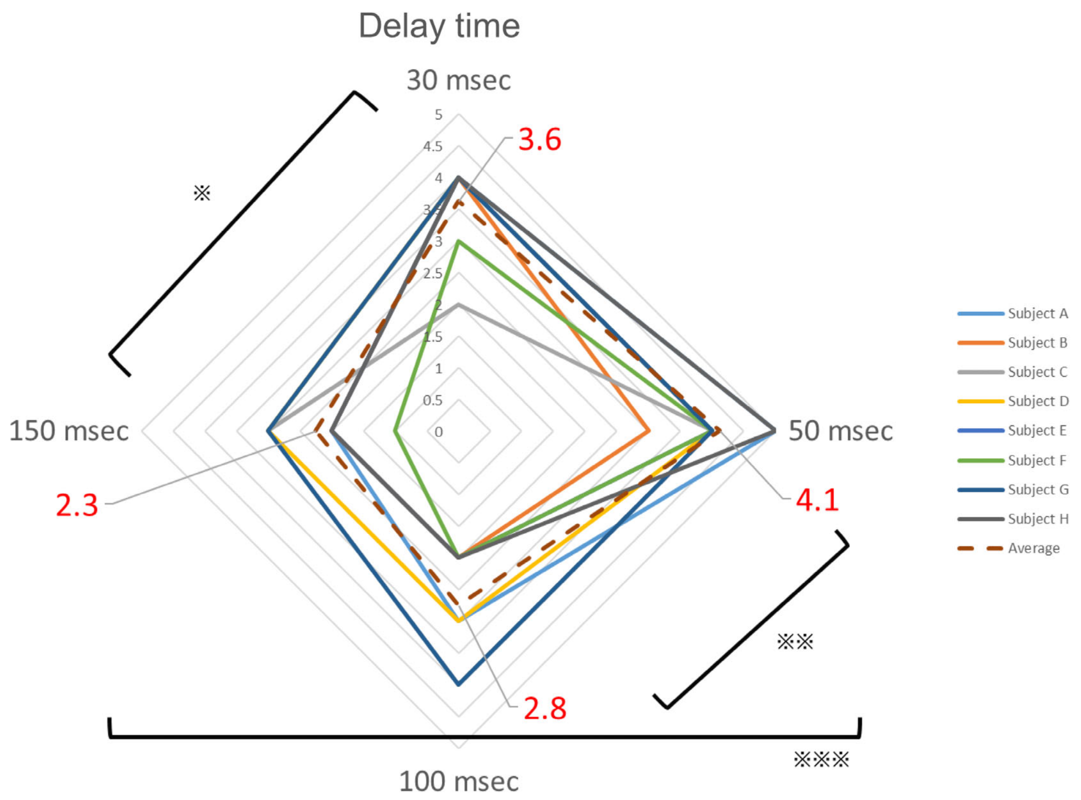


FIGURE 3 Verification results of delay time. The dashed line represents the average value.

the experiment, for euthanization purpose, cardiac arrest was induced with deep anesthesia, de-bleeding, and an intravenous infusion of KCl-saturated water (Approval No. AE01-2022-030).

2.5 | Evaluation

The following five-level ratings were established for both delay time and image compression (Supplementary Table S1). Subjects were asked to answer questions subjectively after completing each task involving a change in the delay time or a change in the image compression. (1) Completely impossible, (2), Somewhat possible, but almost impossible, (3) Uncomfortable, but possible, (4) Somewhat of a discomfort, but possible, and (5) PossibleWe also included a column where respondents could freely describe anything they noticed during the task.

2.6 | Statistical analysis

The software used was EZR.[6] The Kolmogorov–Smirnov test was used to test for normality, and the Bartlett test was used to test for equal variance. One-way analysis of variance was used to analyze the data, and statistical significance was determined with $P < .05$.

3 | RESULTS

For forceps, we used monopolar curved scissors for the right hand, and a bipolar fenestrated forceps or a bipolar Maryland forceps for the left hand; the difference in the type of forceps or device did not affect the results.

3.1 | Evaluation of the delay time

The mean questionnaire ratings for the eight subjects were 3.6 at 30 milliseconds, 4.1 at 50 milliseconds, 2.8 at 100 milliseconds, and 2.3 at 150 milliseconds. Significant differences were found in the scores between 30–150, 50–100, and 50–150 milliseconds (* $P = .005$, ** $P = .005$, *** $P = .0002$) (Figure 3). In postoperative comments, more subjects reported difficulty with the procedure as the delay was prolonged.

3.2 | Evaluation of the image compression

The mean questionnaire ratings for the eight subjects were 4.8 at a bit rate of 120 Mbps, 4.4 at 60 Mbps, 4.1 at 30 Mbps, 4.5 at 20 Mbps, and 4.0 at 10 Mbps (Figure 4). No significant differences were found between the items.

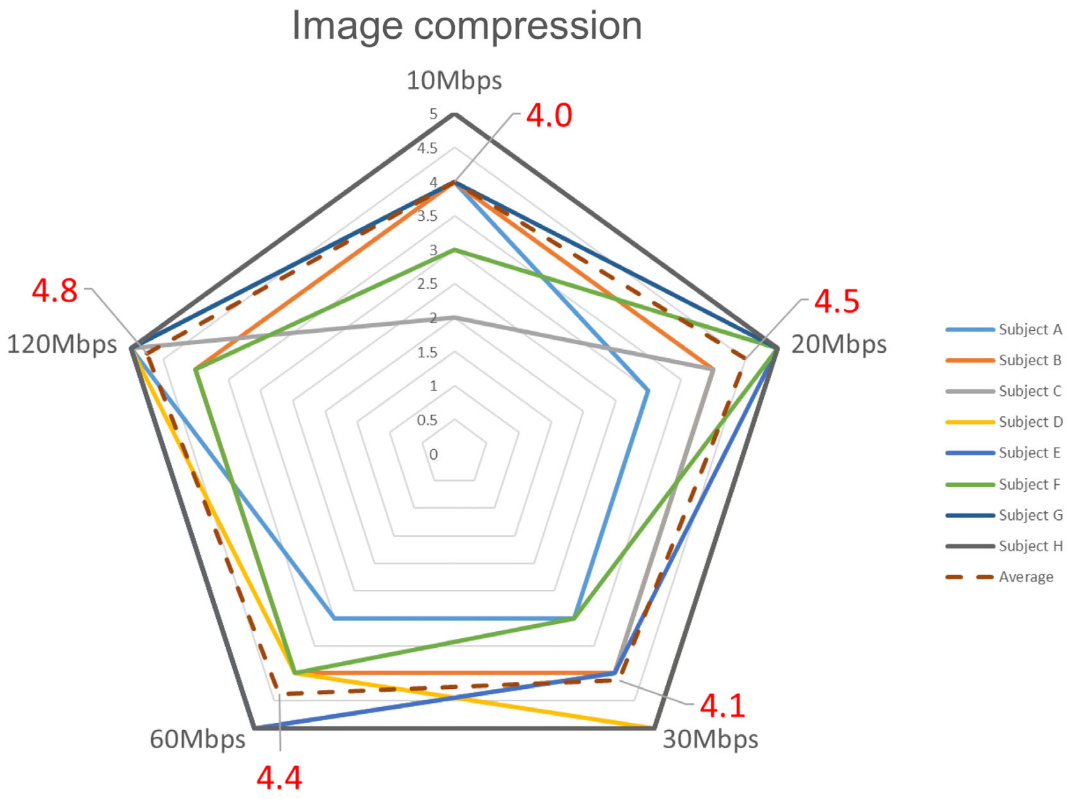


FIGURE 4 Verification results of image compression. The dashed line represents the average value.

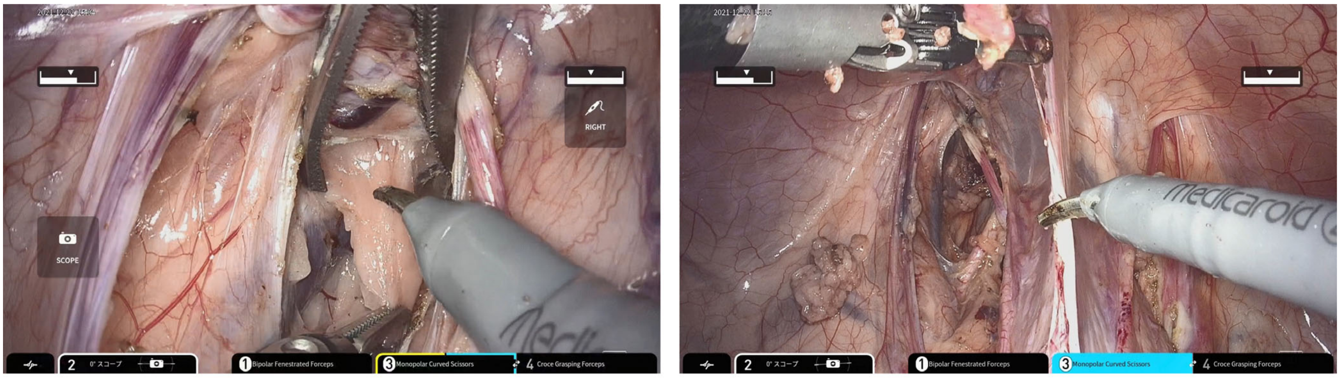
Postoperative comments indicated that although there were scattered subjects who felt that the image quality had deteriorated, they often thought that the surgical procedure itself had not been affected.

4 | DISCUSSION

In this verification, insertion of delay time up to 50 milliseconds had little effect on the surgical technique. In addition, image compression by encoder/decoder to a limit of 10 Mpbs did not affect the surgical procedure. It is significant that this study, using a biological model, was able to evaluate the acceptable level of delay and image degradation caused by image compression and restoration processing, which is necessary for the introduction of telesurgery.

In recent years, surgical procedures have become more diverse and complex with the development of technology, and the content of surgical procedures has significantly changed. In particular, technological innovations in approaches have led to a rapid increase in the number of robotic surgeries using surgical-assist robots. In Japan, robotic surgery for total prostatectomy was covered by insurance in 2012, and the use of da Vinci® (Intuitive Surgical) and other robots began to spread throughout the country. Subsequent insurance revisions have expanded the indications to various fields, including gastrointestinal surgery, respiratory surgery, and gynecology. Although telesurgery has been studied in many countries since the 1970s, many issues have arisen, including the economics of dedicated communication lines, communication safety, and communication delays. In recent years, communication networks have been improved, and communication delays and security issues are being resolved.[7] With the widespread use of optical networks and reports of remote robotic surgery using 5G lines, there are high expectations for robotic telesurgery using commercial lines.[8]

The biggest hurdle for telesurgery is the problem of delay. The delay time experienced by the surgeon consists of three elements: communication delay, information processing delay, and robot delay. Of these transmissions, the most significant cause of delay is image transmission, which contains a large amount of information. The delay occurs when this video information is compressed and restored by the information processing technology of the encoder/decoder and transmitted over the communication line. A number of studies have already reported on the extent to which people can tolerate such delays. Nguan et al. reported a telerobotic surgery using animals, which resulted in a delay time of 347 ± 46 milliseconds.[9]



(A) 10Mbps (B) 120Mbps

FIGURE 5 (A) Rectal resection, surgical view at 10 Mbps bit rate (B) Rectal resection, surgical view at 120 Mbps bit rate

Generally, a delay time of 100 milliseconds or longer is considered to affect operability, and a delay time exceeding 100 milliseconds is considered to make surgery difficult.[10,11] However, there are reports that surgical procedures can be performed without intraoperative complications even with a delay time of 135–140 milliseconds,[12] so the exact threshold has not been established. In this study, delays of up to 50 milliseconds were considered acceptable, while delays exceeding 100 milliseconds affected the surgical procedure, and many subjects found it difficult to continue. Therefore, this threshold value is likely to be used as a reference value in the future spread of teleoperation.

No significant differences were found among the items for image compression. Although some subjects felt a change in the video when the compression rate was increased to 10 Mbps, which is the limit of the encoder/decoder used, the surgery could continue in both cases. Presenting images captured from surgical videos at 10 and 120 Mbps, it can be seen that no obvious changes due to image compression can be felt. (Figure 5). Ebihara et al. reported that telerobotic surgery can be performed safely with a communication bandwidth of 150 Mbps or higher, and even when the communication bandwidth is insufficient, image degradation can be avoided by considering the image compression ratio.[13] In addition, Edward et al. reported that telesurgery can be performed at bit rates of 8–20 Mbps.[14] Therefore, there is a possibility that remote robotic surgery can be performed even when the communication bandwidth is not sufficient, as in the case of mobile communication.

The realization of routine remote surgery will improve access to medical care by enabling local patients to undergo highly difficult surgeries requiring specialist skills right at their local hospitals.[15] Also, in areas with few surgeons, young surgeons can receive remote surgical support and guidance from specialists at distant flagship hospitals via a communication system.[16] To establish such a system, it is necessary to select an economically superior communication network that has sufficient communication bandwidth and communication security. In general, the wider the bandwidth of the line, the more stable the communication and robot operation, but the higher the communication fee. Since the amount of bandwidth required by each surgical support robot differs, it is necessary to prepare a line that can secure communication bandwidth exceeding the amount of bandwidth required by each robot, on a priority basis.

The validation of the image compression process in this study yielded acceptable ranges for telesurgery using hinotori™. It is anticipated that technological advancements will lead to the development of various types of robotic systems, communication environments, and compression and restoration processing techniques. Since the communication delay may differ depending on the combination of these systems, it is desirable to study this issue in the various different systems. In addition, the benefits of telesurgery being widely recognized by society is not merely a technical issue. In addition to absolute safety, it is considered necessary to examine the ethical and economic rationale for meeting society's needs in this manner.

5 | LIMITATIONS

Due to limited validation time, the number of subjects and the number of pigs used in the experiment were small. It was difficult to standardize the procedures for either the gastrectomy or the rectal resection. Many subjects were not familiar with the operation of hinotori™. The economics of communication could not be examined.

6 | CONCLUSION

In remote robotic surgery using hinotori™, image compression and delay time are largely acceptable and surgery can be safely performed.

AUTHOR CONTRIBUTION

All authors agree to the contents of the manuscript.

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DATA AVAILABILITY STATEMENT

Research data are not shared.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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