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2 Original Article

- 3 **Title:** Tele-assessment of bandwidth limitation for remote robotics surgery
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- 9
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- 11 robotic surgery, remote robotics surgery, packet loss, communication delay
- 12
- 13
- 14
- 15

1	Abstrac	t

Purpose

3	This study investigated the communication bandwidth (CB) limitation for remote robotics surgery
4	(RRS) using hinotori TM (Medicaroid, Kobe, Japan).
5	Methods
6	The operation rooms of the Hokkaido University Hospital and Kyushu University Hospital were
7	connected using the Science Information NETwork (SINET). The minimum required CB for the RRS was
8	verified by decreasing the CB from 500 to 100 Mbps. Ten surgeons were tested on the task (intracorporeal
9	suturing) at different levels of video compression (VC) amounts (VC1: 120 Mbps, VC2: 40 Mbps, VC3:
10	20 Mbps) with the minimum required CB and assessed based on the task completion time, Global
11	Evaluative Assessment of Robotic Skills (GEARS), and System and Piper Fatigue Scale-12 (PFS-12).
12	Results
13	Packet loss was observed at 3–7% and image degradation was observed at 145 Mbps CB. The task
14	performance with VC1 was significantly worse than that with VC2 and VC3 regarding task completion
15	time (VC1 vs. VC2, P=0.032; VC1 vs. VC3, P=0.032), GEARS (VC1 vs. VC2; P=0.029, VC1 vs. VC3;
16	P=0.031), and PFS-12 (VC1 vs. VC2; P=0.032, VC1 vs. VC3; P=0.032) with 145 Mbps.
17	Conclusion
18	We concluded that RRS using hinotori TM requires a CB \geq 150 Mbps; when there is insufficient CB,

- 1 RRS can be continued by compressing the image.

1 Text

2 Introduction

3	In recent years, the development of high-speed, high-capacity communication technology using
4	optical fiber and 5th generation mobile communication systems (5G), as well as the development of new
5	surgical robots, has made remote surgery a reality [1]. One of the advantages of remote robotics surgery
6	(RRS) is that it can reduce the physical, mental, and financial burden on patients and surgeons by
7	reducing their travel requirements. However, there are still many problems to be solved to implement
8	RRS in society, and one of them is the establishment of a stable communication environment. The
9	occurrence of communication delays or significant packet loss during surgery leads to the distribution of
10	images and inadequate robot functions, which are major obstacles to safe surgery [2-5]. To avoid this, it is
11	essential to determine the communication bandwidth (CB) required for safe and stable telecommunication
12	according to the amount of video data and operation data for each surgical robot. The purpose of this
13	study was to determine the required CB for RRS using hinotori TM , a novel surgical robot made in Japan.
14	Setting the required CB is essential to ensure future implementation.
15	

16 Materials and methods

The minimum required CB for RRS using hinotoriTM was verified by gradually decreasing the CB
from 500 to 100Mbps. We measured the communication round-trip time (RTT; the time in milliseconds

1	from the time the switch on the surgeon cockpit side sends a request to the time the response is received
2	from the switch on the operation unit side), jitter (variation in latency of packet flow), and packet loss (the
3	fraction of the total transmitted packets that did not arrive at the receiver) for each CB. Ten skilled
4	surgeons including 5 gastroenterological surgeon, 2 urologist, 2 gynecologist and a thoracic surgeon were
5	participated in this experiment. They all had sufficient experience in laparoscopic surgery, and experience
6	of robotic surgery.
7	After we found the minimum required bandwidth, the participants were tested on a standard task
8	(intracorporeal suturing) based on the Fundamentals of Laparoscopic Surgery (FLS) curriculum [6] using
9	different video compression (VC; the process of reducing the total number of bits needed to represent a
10	given image or video sequence) amounts (VC1: 120 Mbps, VC2: 40 Mbps, VC3: 20 Mbps) with the
11	minimum required bandwidth. We measured the RTT, jitter, packet loss for the VC amount, task
12	completion time, and robotic surgical skill using the Global Evaluative Assessment of Robotic Skills
13	(GEARS); subjective evaluation of the surgeon was validated using the System and Piper Fatigue Scale-
14	12 (PFS-12).
15	
16	(1) Network connections
17	The operation rooms of Hokkaido University Hospital and Kyushu University Hospital were
18	connected by SINET5 (Science Information NETwork) [7] (Fig. 1). SINET5 is a non-commercial science

1	information network designed and operated by the National Institute of Informatics and provides a nation-
2	wide 100-Gbps backbone for about 1,000 universities and research institutes throughout Japan. For this
3	investigation a virtual private communication circuit was established between the two hospitals along the
4	Japan Sea side, and its circuit distance was about 2,000km on a map basis and about 2,600 km on an
5	optical-fiber-length basis. The CBs of the circuit were set up in the range of 500Mbps to 100Mbps by
6	specifying the rate limits so as to drop information packets if the usage rate of the circuit exceeds the
7	specified rate limit. Communication information was compressed and decompressed using certain
8	encoder and decoder that is evaluated by Medicaroid (Medicaroid Corporation, Kobe, Japan). The
9	encoders and decoders used in this study employ H.265 [8], which is a high compression technology that
10	enables ultra-short delay video transmission and has been applied to ultra-short delay live broadcasting. A
11	raw video is a sequence of images, its size makes it impractical to store or transfer. VC takes advantage of
12	the fact that the frames in a video sequence are highly correlated in time and reduces spatial and temporal
13	redundancy so that as few bits as possible are used to represent the video sequence. Modern standard
14	video compression algorithms such as H.265 are psycho-visually optimized and compress the video data
15	in such a way that quality and detail reduction is, as far as possible, invisible to human perception. To
16	evaluate the communication delay during RRS, we measured RTT of the network line and the packet loss
17	of image signals. RTT is composed of communication line delay (SINET) (Fig. 2).

1 (2) Robot system

2	We used a hinotori TM surgical robot system (Medicaroid Corporation, Kobe, Japan). This is the first
3	made-in-Japan robotic system, which recently (August 2020) received regulatory approval from the
4	Japanese Ministry of Health, Labor, and Welfare. A Karl Storz TM 3D endoscope system (Karl Storz,
5	Tuttlingen, Germany) was installed in the system.
6	
7	(3) Task: intracorporeal suturing
8	At least three throws of the suture were made, including one double throw and two single throws.
9	The time was measured starting when the instrument appeared on the monitor and ended when the suture
10	material and needle were cut. The task completion time and results of the technical evaluation using
11	GEARS were recorded [9]. The technical evaluation was conducted by two physicians certified in the
12	endoscopic surgical skill qualification system of the Japan Society for Endoscopic Surgery (JSES) [10].
13	The subjective evaluation of the surgeon was validated using PFS-12 [11].
14	
15	(4) Statistical analysis
16	Each test score was compared between groups using the Mann-Whitney U test for continuous
17	variables. Statistical significance was set at P<0.05. Statistical analysis was performed using the JMP [®] 15
18	software (SAS Institute Inc., Cary, NC, USA).

2	Results
3	(1) Minimum required CB for RRS using the hinotori ^{TM}
4	Figure 3 shows an example of the network communication delay, packet loss, and jitter for each CB (500-
5	300–200–150–145 Mbps). Ten surgeon tried simple task such as ring movement in each CB. At 145 Mbps
6	CB, the packet loss was noticeable (3.0–7.0%), and image degradation was observed (Fig. 4.) However,
7	RTT and jitter did not change (RTT, 30–30.4 ms; jitter, 0–0.35 ms).
8	
9	(2) Task: intracorporeal suturing
10	Five surgeon tried simulation of intracorporeal suturing in CB of 145Mbps which was revealed to be the
11	minimum required CB for the robot system in the former experiment. Concerning changes in network
12	communication delay in VC2 and VC3, RTT and jitter did not change (RTT, 30–31.5 ms; jitter, 0–0.6 ms),
13	and no packet loss was observed (Fig. 5). The total amount of communication data (including the robot
14	control signal) under a communication bandwidth of 145 Mbps was 130–155 Mbps for VC1, 50–65 Mbps
15	for VC2, and 35–40 Mbps for VC3 (Fig.6). The intracorporeal suturing completion time (VC1:
16	667.4±56.4 s, VC2: 275.8±73.9 s, and VC3: 236.4±42.5 s) was significantly longer in VC1 compared to
17	those in VC2 and VC3 (VC1 vs. VC2, P=0.009; VC1 vs. VC3, P=0.009; VC2 vs. VC3, P=0.209) (Fig.
18	7a). Regarding the GEARS score (VC1, 17.4 ± 1.7 ; VC2, 26.6 ± 3.4 ; VC3, 27.2 ± 1.5), it was

1	significantly lower in VC1 than in VC2 and VC3 (VC1 vs. VC2, P=0.008; VC1 vs. VC3, P=0.009; VC2
2	vs. VC3, P=0.829) (Fig. 7b). The PFS-12 score (VC1, 98.8±18.1; VC2, 34.4±20.5; VC3, 33.2±28.1) was
3	significantly higher in VC1 than in VC2 and VC3 (VC1 vs. VC2, P=0.009; VC1 vs. VC3, P=0.009; VC2
4	vs. VC3, P=0.917) (Fig. 7c).
5	
6	Discussion
7	In this study, we set up the Japanese-made surgical robot system, hinotori TM , in an operating room
8	2,000 km away from the operator to investigate the feasibility of RRS and confirmed the robot's behavior
9	in an environment where surgery is actually possible. In this SINET connection verification, we confirmed
10	that there was no recognizable communication delay or image degradation at a CB of more than 150 Mbps.
11	Furthermore, it was suggested that image degradation could be avoided by considering the amount of VC,
12	even when the available CB is insufficient.
13	Telemedicine has become an inevitable trend during the development of modern medical technology.
14	Teleconsultation, telediagnosis, mobile wards, remote patient image sharing, remote emergency
15	treatment, image sharing and emergency treatment for stroke, digital operating rooms, and distance
16	education have made considerable progress [12-17]. In particular, the development of RRS has been
17	remarkable. Using the ZEUS robotic system and the Transatlantic Optical Faber Network, Jack
18	Marescaux [18, 19] performed the first clinical remote cholecystectomy. This procedure is also known as

1	Lindbergh surgery and is considered a milestone in telesurgery. Subsequently, 22 telesurgeries were
2	performed at a hospital in North Bay, approximately 400 km north of Hamilton, Canada [20]. Although
3	both surgeries were successful, but the transatlantic connection used an expensive dedicated line (10Mbps
4	CB), while the Canadian clinical case used an Internet Protocol-Virtual Private Network line, a special
5	inter-hospital network developed by the government (15Mbps CB). In the USA, Florida Hospital has
6	successfully performed robot-assisted remote surgery using the Internet. Surgeons in Texas, 1,200 miles
7	away from Florida, remotely controlled a da Vinci robot to operate on a simulated patient via the Internet
8	[21]. In Japan, robotic telesurgical simulation for training was reported by Hashizume et al. [22].
9	Consequently, the underdeveloped information and communication technology was a decisive factor that
10	led to a long hiatus in telesurgery research [23]. The recent development of high-speed, high-capacity
11	communication technology using optical fiber and 5G, as well as the development of new surgical robots,
12	is making remote surgery a reality [24]. The bandwidth of the optical fiber and 5G network were 1 Gbps,
13	which is comparable to the bearing capacity of the Internet and 100 times wider than that of the satellite
14	network [1]. In the future, it is expected that robotic surgery using the Internet will further develop with
15	the evolution of technology.
16	However, there are many problems to be solved in RRS, one of which is the establishment of a stable
17	communication environment. Communication delays during RRS can be a major obstacle to safe surgical
18	procedures [2-5]. In general, regarding the transmission delay, it has been reported that operability

1	decreases when the delay time perceived by the surgeon exceeds 200 ms, errors increase when the delay
2	time exceeds 300 ms [25, 26], and work becomes almost impossible when the delay time exceeds 700 ms
3	[27]. Many reports suggest that the delay time should be less than 200 ms, ideally less than 100 ms, for
4	normal robot operation [28, 29].
5	In this study, it was possible to operate with minimal delay (<30 ms) for all CBs; however, image
6	degradation was observed in the 145 Mbps CB. When robot control signals and audio signals were
7	included in addition to the image signals, the traffic from all the signals exceeded 145 Mbps, and image
8	degradation was observed. Because of the degraded images, the task completion time increased, and the
9	surgeon's fatigue increased. The reason why image degradation rather than image delay occurred when
10	reducing CB was thought to be the adoption of traffic policing, which cuts off some of the traffic that
11	exceed the rate limit on SINET lines. At 145 Mbps, by changing the VC amount (VC 2: 40 Mbps, VC 3:
12	20 Mbps), image degradation disappeared at the same CB, and we could not discern any decrease in
13	image quality. In addition to image degradation, information and communication processing technology
14	to compress and decompress transmission data is also important. The largest volume of transmission
15	signals in the RRS is the video signal, which is strongly affected by the CB. Therefore, information and
16	compression processing technologies are essential; however, the compression and decompression
17	processes also cause delays. Because there is a trade-off between the compression ratio and time required
18	for compression and decompression, it is necessary to develop encoders and decoders that achieve high

compression and low delay. In this study, excessive image capacity load might cause image degradation,

2	and the amount of VC needed to be adjusted as a countermeasure.
3	In this study, despite the long communication distance of approximately 4000 km round trip, we
4	were able to communicate 3D 2K images without image degradation with an RTT of 30 ms which hardly
5	affected the surgeon's performance. Furthermore, even with a CB of 145 Mbps, we were able to perform
6	the task without any image degradation or delay using image compression technology. In the future, the
7	limitations of CB may be overcome by the development of encoders, decoders, and 5G communication
8	technologies that enable low-latency transmission of high-precision images, such as 8K and 16K.
9	In this study, we demonstrated that hinotori TM can be used in commercial communications by
10	selecting a bandwidth type of service of more than 150 Mbps. Currently, there are two types of
11	commercial communication networks, open and closed networks, which differ in their degree of security
12	assurance, communication quality, and cost. In RRS, it is important to select a communication network
13	based on the premise of sufficient communication quality and security while considering economic
14	efficiency. For future clinical applications of RRS, it would be desirable to develop guidelines for optimal
15	communication systems focusing on safety, ethics, and costs.
16	In recent years, 5G communication technology has been reported to have advantages such as high
17	speed and large capacity communication, high mobility, multiple connections, and wide bandwidth, which
18	will be beneficial for robots that require a wide bandwidth for high-quality transmission, such as 4K/8K

1	video [1]. The 5G network has many advantages, such as wider bandwidth and lower latency time than
2	the previous 4G network. Furthermore, unlike the wired Internet, the 5G wireless network has high
3	mobility and eliminates the regional restriction of special network cables. Therefore, RSS is expected to
4	be realized in isolated islands and disaster areas where it is difficult to lay wired Internet cables. In
5	addition, surgeries performed during the current coronavirus disease 2019 pandemic era need to avoid
6	infection crises due to the flow of people. In this situation, RSS using 5G is expected to be able to support
7	remote surgeries in regional hospitals throughout Japan and help train young surgeons.
8	This study has several limitations. Because of the limited duration of the experiment, the number of
9	tasks was small, and the time to practice the robot operation was short. The image quality was evaluated
10	based on the surgeon's impression, and no objective data analysis was conducted. In the future, remote
11	surgery using high-precision images is possible, and a universal image evaluation method is necessary.
12	
13	Conclusion
14	RRS using the novel hinotori TM surgical robot system can be performed safely if the CB is ≥ 150
15	Mbps. RRS can be implemented in society using currently available commercial communication
16	networks.
17	

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6	
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2	Figure legends
3	
4	Fig. 1 Schema of network connection for remote robotics surgery
5	The operation rooms of Hokkaido University Hospital and Kyushu University Hospital (network
6	communication distance of nearly 2,000 km) were connected by SINET.
7	SINET; Science Information NETwork, HUH; Hokkaido University Hospital, KUH; Kyushu University
8	Hospital
9	
10	Fig. 2 Network system
11	Round trip time (RTT) is composed of communication line delay (SINET). SINET; Science
12	Information NETwork
13	
14	Fig. 3 The packet loss and jitter for communication bandwidths of 500 Mbps, 300 Mbps, 200 Mbps, 150
15	Mbps, and 145 Mbps
16	At 145 Mbps, the packet loss was noticeable (3–7 %); however, the round-trip time (RTT) and jitter
17	did not change (RTT, 30-30.4 ms; jitter, 0-0.35 ms)
18	

1	Fig. 4 Operation image from 145-Mbps communication bandwidth
2	At 145 Mbps, image degradation was observed
3	
4	Fig. 5 Comparison of round-trip time (RTT), packet loss, and jitter depending on the video compression
5	(VC) amount
6	At VC 1 (120 Mbps), packet loss was between 3% and 7%. At VC 2 (40 Mbps) and VC 3 (20 Mbps),
7	packet loss was not observed. RTT and jitter showed no changes (RTT, 30–31.5 ms, jitter, 0–1.0 ms) for all
8	VC
9	
10	Fig. 6 Total amount of communication data under communication bandwidth of 145 Mbps
11	The total amount of communication data (including the robot control signal) was 130-155 Mbps at
12	video compression (VC) 1 (120 Mbps), 50-65 Mbps at VC 2 (40 Mbps), 35-40 Mbps at VC 3 (20
13	Mbps)
14	
15	Fig. 7 Intracorporeal suturing completion time, and the robotic skill evaluation using the Global Evaluative
16	Assessment of Robotic Skills (GEARS), and the subjective evaluation of the surgeon was validated using
17	the System and Piper Fatigue Scale-12 (PFS-12)
18	a. Intracorporeal suturing completion time: VC1 significantly prolonged the task completion time

2	were significantly lower than those with VC2 and VC3 (P=0.008 and P=0.009, respectively). c. PFS-12
3	scores with VC1 were significantly higher than those with VC2 and VC3 ($P= 0.009$ and $P=0.009$,
4	respectively).

compared to that with VC2 and VC3 (P= 0.009 and P=0.009, respectively). b. GEARS scores with VC1

5 VC: video compression (VC1, 120 Mbps; VC2, 40 Mbps; VC3, 20 Mbps)













