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Original Article

Title: Tele-assessment of bandwidth limitation for remote robotics surgery

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Short running head: Tele-assessment of bandwidth limitation for RRS

Keywords

robotic surgery, remote robotics surgery, packet loss, communication delay

Abstract

Purpose

This study investigated the communication bandwidth (CB) limitation for remote robotics surgery (RRS) using hinotori^{TM} (Medicaroid, Kobe, Japan).

Methods

The operation rooms of the Hokkaido University Hospital and Kyushu University Hospital were connected using the Science Information NETwork (SINET). The minimum required CB for the RRS was verified by decreasing the CB from 500 to 100 Mbps. Ten surgeons were tested on the task (intracorporeal suturing) at different levels of video compression (VC) amounts (VC1: 120 Mbps, VC2: 40 Mbps, VC3: 20 Mbps) with the minimum required CB and assessed based on the task completion time, Global Evaluative Assessment of Robotic Skills (GEARS), and System and Piper Fatigue Scale-12 (PFS-12).

Results

Packet loss was observed at 3–7% and image degradation was observed at 145 Mbps CB. The task performance with VC1 was significantly worse than that with VC2 and VC3 regarding task completion time (VC1 vs. VC2, P=0.032; VC1 vs. VC3, P=0.032), GEARS (VC1 vs. VC2; P=0.029, VC1 vs. VC3; P=0.031), and PFS-12 (VC1 vs. VC2; P=0.032, VC1 vs. VC3; P=0.032) with 145 Mbps.

Conclusion

We concluded that RRS using hinotori^{TM} requires a CB ≥150 Mbps; when there is insufficient CB,

RRS can be continued by compressing the image.

Text

Introduction

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

Materials and methods

The minimum required CB for RRS using hinotori^{TM} was verified by gradually decreasing the CB from 500 to 100Mbps. We measured the communication round-trip time (RTT; the time in milliseconds from the time the switch on the surgeon cockpit side sends a request to the time the response is received from the switch on the operation unit side), jitter (variation in latency of packet flow), and packet loss (the fraction of the total transmitted packets that did not arrive at the receiver) for each CB. Ten skilled surgeons including 5 gastroenterological surgeon, 2 urologist, 2 gynecologist and a thoracic surgeon were participated in this experiment. They all had sufficient experience in laparoscopic surgery, and experience of robotic surgery.

After we found the minimum required bandwidth, the participants were tested on a standard task (intracorporeal suturing) based on the Fundamentals of Laparoscopic Surgery (FLS) curriculum [6] using different video compression (VC; the process of reducing the total number of bits needed to represent a given image or video sequence) amounts (VC1: 120 Mbps, VC2: 40 Mbps, VC3: 20 Mbps) with the minimum required bandwidth. We measured the RTT, jitter, packet loss for the VC amount, task completion time, and robotic surgical skill using the Global Evaluative Assessment of Robotic Skills (GEARS); subjective evaluation of the surgeon was validated using the System and Piper Fatigue Scale-12 (PFS-12).

(1) Network connections

The operation rooms of Hokkaido University Hospital and Kyushu University Hospital were connected by SINET5 (Science Information NETwork) [7] (Fig. 1). SINET5 is a non-commercial science information network designed and operated by the National Institute of Informatics and provides a nation-wide 100-Gbps backbone for about 1,000 universities and research institutes throughout Japan. For this investigation a virtual private communication circuit was established between the two hospitals along the Japan Sea side, and its circuit distance was about 2,000km on a map basis and about 2,600 km on an optical-fiber-length basis. The CBs of the circuit were set up in the range of 500Mbps to 100Mbps by specifying the rate limits so as to drop information packets if the usage rate of the circuit exceeds the specified rate limit. Communication information was compressed and decompressed using certain encoder and decoder that is evaluated by Medicaroid (Medicaroid Corporation, Kobe, Japan). The encoders and decoders used in this study employ H.265 [8], which is a high compression technology that enables ultra-short delay video transmission and has been applied to ultra-short delay live broadcasting. A raw video is a sequence of images, its size makes it impractical to store or transfer. VC takes advantage of the fact that the frames in a video sequence are highly correlated in time and reduces spatial and temporal redundancy so that as few bits as possible are used to represent the video sequence. Modern standard video compression algorithms such as H.265 are psycho-visually optimized and compress the video data in such a way that quality and detail reduction is, as far as possible, invisible to human perception. To evaluate the communication delay during RRS, we measured RTT of the network line and the packet loss of image signals. RTT is composed of communication line delay (SINET) (Fig. 2).

(2) Robot system

We used a hinotori™ surgical robot system (Medicaroid Corporation, Kobe, Japan). This is the first made-in-Japan robotic system, which recently (August 2020) received regulatory approval from the Japanese Ministry of Health, Labor, and Welfare. A Karl Storz™ 3D endoscope system (Karl Storz, Tuttlingen, Germany) was installed in the system.

(3) Task: intracorporeal suturing

At least three throws of the suture were made, including one double throw and two single throws. The time was measured starting when the instrument appeared on the monitor and ended when the suture material and needle were cut. The task completion time and results of the technical evaluation using GEARS were recorded [9]. The technical evaluation was conducted by two physicians certified in the endoscopic surgical skill qualification system of the Japan Society for Endoscopic Surgery (JSES) [10]. The subjective evaluation of the surgeon was validated using PFS-12 [11].

(4) Statistical analysis

Each test score was compared between groups using the Mann–Whitney U test for continuous variables. Statistical significance was set at $P<0.05$. Statistical analysis was performed using the JMP® 15 software (SAS Institute Inc., Cary, NC, USA).

Results

(1) Minimum required CB for RRS using the hinotori™

Figure 3 shows an example of the network communication delay, packet loss, and jitter for each CB (500–300–200–150–145 Mbps). Ten surgeon tried simple task such as ring movement in each CB. At 145 Mbps CB, the packet loss was noticeable (3.0–7.0%), and image degradation was observed (Fig. 4.) However, RTT and jitter did not change (RTT, 30–30.4 ms; jitter, 0–0.35 ms).

(2) Task: intracorporeal suturing

Five surgeon tried simulation of intracorporeal suturing in CB of 145Mbps which was revealed to be the minimum required CB for the robot system in the former experiment. Concerning changes in network communication delay in VC2 and VC3, RTT and jitter did not change (RTT, 30–31.5 ms; jitter, 0–0.6 ms), and no packet loss was observed (Fig. 5). The total amount of communication data (including the robot control signal) under a communication bandwidth of 145 Mbps was 130–155 Mbps for VC1, 50–65 Mbps for VC2, and 35–40 Mbps for VC3 (Fig.6). The intracorporeal suturing completion time (VC1: 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 those in VC2 and VC3 (VC1 vs. VC2, $P=0.009$; VC1 vs. VC3, $P=0.009$; VC2 vs. VC3, $P=0.209$) (Fig. 7a). Regarding the GEARS score (VC1, 17.4 ± 1.7; VC2, 26.6 ± 3.4; VC3, 27.2 ± 1.5), it was significantly lower in VC1 than in VC2 and VC3 (VC1 vs. VC2, P=0.008; VC1 vs. VC3, P=0.009; VC2 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 significantly higher in VC1 than in VC2 and VC3 (VC1 vs. VC2, P=0.009; VC1 vs. VC3, P=0.009; VC2 vs. VC3, P=0.917) (Fig. 7c).

Discussion

In this study, we set up the Japanese-made surgical robot system, hinotori™, in an operating room 2,000 km away from the operator to investigate the feasibility of RRS and confirmed the robot's behavior in an environment where surgery is actually possible. In this SINET connection verification, we confirmed that there was no recognizable communication delay or image degradation at a CB of more than 150 Mbps. Furthermore, it was suggested that image degradation could be avoided by considering the amount of VC, even when the available CB is insufficient.

Telemedicine has become an inevitable trend during the development of modern medical technology. Teleconsultation, telediagnosis, mobile wards, remote patient image sharing, remote emergency treatment, image sharing and emergency treatment for stroke, digital operating rooms, and distance education have made considerable progress [12-17]. In particular, the development of RRS has been remarkable. Using the ZEUS robotic system and the Transatlantic Optical Faber Network, Jack Marescaux [18, 19] performed the first clinical remote cholecystectomy. This procedure is also known as

Lindbergh surgery and is considered a milestone in telesurgery. Subsequently, 22 telesurgeries were performed at a hospital in North Bay, approximately 400 km north of Hamilton, Canada [20]. Although both surgeries were successful, but the transatlantic connection used an expensive dedicated line (10Mbps CB), while the Canadian clinical case used an Internet Protocol-Virtual Private Network line, a special inter-hospital network developed by the government (15Mbps CB). In the USA, Florida Hospital has successfully performed robot-assisted remote surgery using the Internet. Surgeons in Texas, 1,200 miles away from Florida, remotely controlled a da Vinci robot to operate on a simulated patient via the Internet [21]. In Japan, robotic telesurgical simulation for training was reported by Hashizume et al. [22]. Consequently, the underdeveloped information and communication technology was a decisive factor that led to a long hiatus in telesurgery research [23]. The recent development of high-speed, high-capacity communication technology using optical fiber and 5G, as well as the development of new surgical robots, is making remote surgery a reality [24]. The bandwidth of the optical fiber and 5G network were 1 Gbps, which is comparable to the bearing capacity of the Internet and 100 times wider than that of the satellite network [1]. In the future, it is expected that robotic surgery using the Internet will further develop with the evolution of technology.

However, there are many problems to be solved in RRS, one of which is the establishment of a stable communication environment. Communication delays during RRS can be a major obstacle to safe surgical procedures [2-5]. In general, regarding the transmission delay, it has been reported that operability decreases when the delay time perceived by the surgeon exceeds 200 ms, errors increase when the delay time exceeds 300 ms [25, 26], and work becomes almost impossible when the delay time exceeds 700 ms [27]. Many reports suggest that the delay time should be less than 200 ms, ideally less than 100 ms, for normal robot operation [28, 29].

In this study, it was possible to operate with minimal delay (<30 ms) for all CBs; however, image degradation was observed in the 145 Mbps CB. When robot control signals and audio signals were included in addition to the image signals, the traffic from all the signals exceeded 145 Mbps, and image degradation was observed. Because of the degraded images, the task completion time increased, and the surgeon’s fatigue increased. The reason why image degradation rather than image delay occurred when reducing CB was thought to be the adoption of traffic policing, which cuts off some of the traffic that exceed the rate limit on SINET lines. At 145 Mbps, by changing the VC amount (VC 2: 40 Mbps, VC 3: 20 Mbps), image degradation disappeared at the same CB, and we could not discern any decrease in image quality. In addition to image degradation, information and communication processing technology to compress and decompress transmission data is also important. The largest volume of transmission signals in the RRS is the video signal, which is strongly affected by the CB. Therefore, information and compression processing technologies are essential; however, the compression and decompression processes also cause delays. Because there is a trade-off between the compression ratio and time required 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, and the amount of VC needed to be adjusted as a countermeasure.

In this study, despite the long communication distance of approximately 4000 km round trip, we were able to communicate 3D 2K images without image degradation with an RTT of 30 ms which hardly affected the surgeon's performance. Furthermore, even with a CB of 145 Mbps, we were able to perform the task without any image degradation or delay using image compression technology. In the future, the limitations of CB may be overcome by the development of encoders, decoders, and 5G communication technologies that enable low-latency transmission of high-precision images, such as 8K and 16K.

In this study, we demonstrated that hinotori™ can be used in commercial communications by selecting a bandwidth type of service of more than 150 Mbps. Currently, there are two types of commercial communication networks, open and closed networks, which differ in their degree of security assurance, communication quality, and cost. In RRS, it is important to select a communication network based on the premise of sufficient communication quality and security while considering economic efficiency. For future clinical applications of RRS, it would be desirable to develop guidelines for optimal communication systems focusing on safety, ethics, and costs.

In recent years, 5G communication technology has been reported to have advantages such as high speed and large capacity communication, high mobility, multiple connections, and wide bandwidth, which will be beneficial for robots that require a wide bandwidth for high-quality transmission, such as 4K/8K video [1]. The 5G network has many advantages, such as wider bandwidth and lower latency time than the previous 4G network. Furthermore, unlike the wired Internet, the 5G wireless network has high mobility and eliminates the regional restriction of special network cables. Therefore, RSS is expected to be realized in isolated islands and disaster areas where it is difficult to lay wired Internet cables. In addition, surgeries performed during the current coronavirus disease 2019 pandemic era need to avoid infection crises due to the flow of people. In this situation, RSS using 5G is expected to be able to support remote surgeries in regional hospitals throughout Japan and help train young surgeons.

This study has several limitations. Because of the limited duration of the experiment, the number of tasks was small, and the time to practice the robot operation was short. The image quality was evaluated based on the surgeon's impression, and no objective data analysis was conducted. In the future, remote surgery using high-precision images is possible, and a universal image evaluation method is necessary.

Conclusion

RRS using the novel hinotori^{TM} surgical robot system can be performed safely if the CB is ≥150 Mbps. RRS can be implemented in society using currently available commercial communication networks.

Acknowledgments

This study was conducted as part of the Advanced Telemedicine Network Research Project of the Japan Agency for Medical Research and Development (AMED), and we are grateful for the financial support. We thank all physicians including gastroenterological and thoracic surgeon, urologist, gynecologist and engineers participating in this study.　We would also like to express our deepest gratitude to the Medicaroid Corporation for their cooperation in the experiments.

Disclosure

This work was supported by a grant from the Japan Agency for Medical Research and Development (AMED) (Grant Number 21hs0122001h0002).

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PMID: 24671353

Figure legends

Fig. 1 Schema of network connection for remote robotics surgery

The operation rooms of Hokkaido University Hospital and Kyushu University Hospital (network communication distance of nearly 2,000 km) were connected by SINET.

SINET; Science Information NETwork, HUH; Hokkaido University Hospital, KUH; Kyushu University Hospital

Fig. 2 Network system

Round trip time (RTT) is composed of communication line delay (SINET). SINET; Science Information NETwork

Fig. 3 The packet loss and jitter for communication bandwidths of 500 Mbps, 300 Mbps, 200 Mbps, 150 Mbps, and 145 Mbps

At 145 Mbps, the packet loss was noticeable (3–7 %); however, the round-trip time (RTT) and jitter did not change (RTT, 30-30.4 ms; jitter, 0–0.35 ms)

Fig. 4 Operation image from 145-Mbps communication bandwidth

At 145 Mbps, image degradation was observed

Fig. 5 Comparison of round-trip time (RTT), packet loss, and jitter depending on the video compression (VC) amount

At VC 1 (120 Mbps), packet loss was between 3% and 7%. At VC 2 (40 Mbps) and VC 3 (20 Mbps), packet loss was not observed. RTT and jitter showed no changes (RTT, 30–31.5 ms, jitter, 0–1.0 ms) for all VC

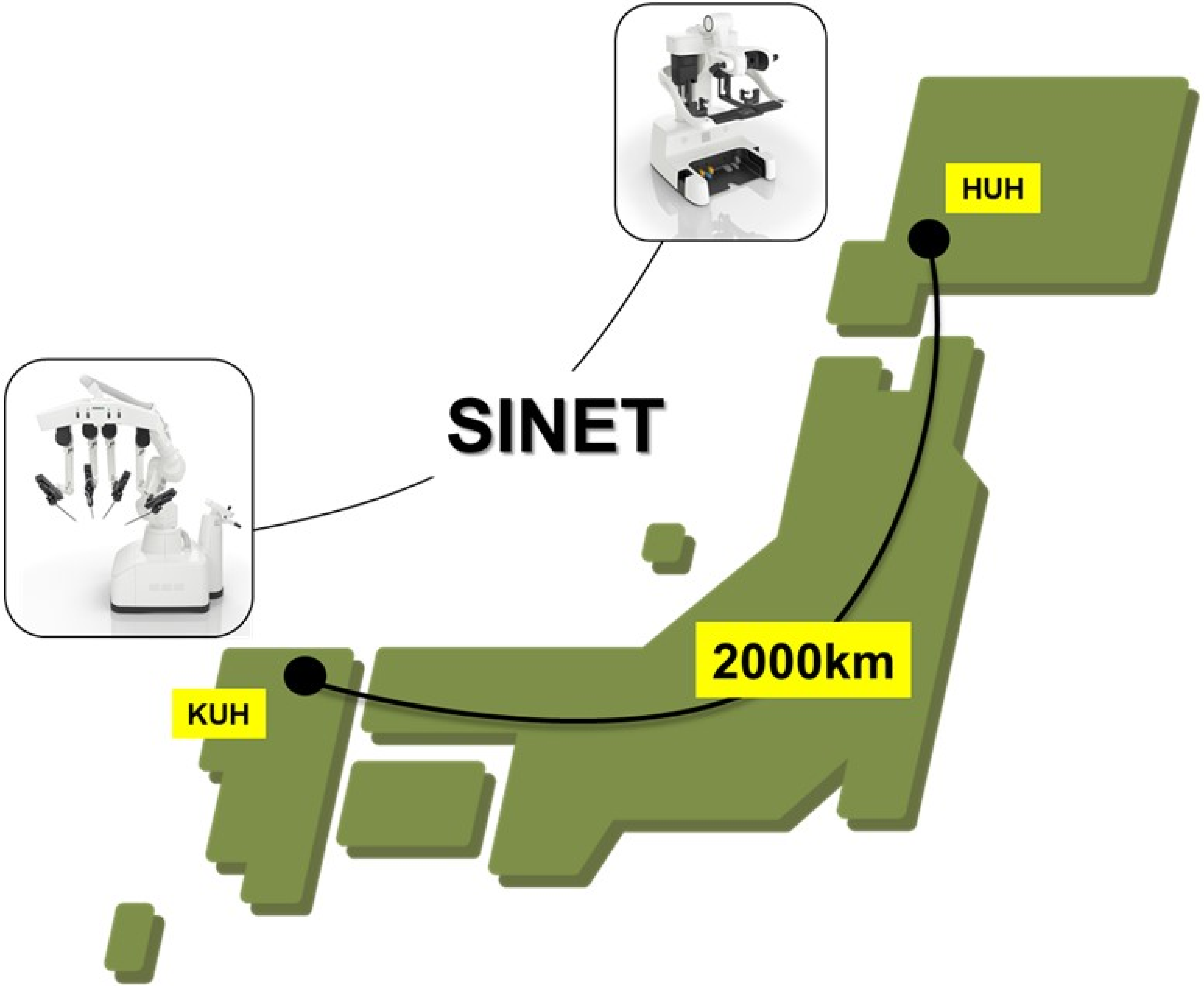
Fig. 6 Total amount of communication data under communication bandwidth of 145 Mbps

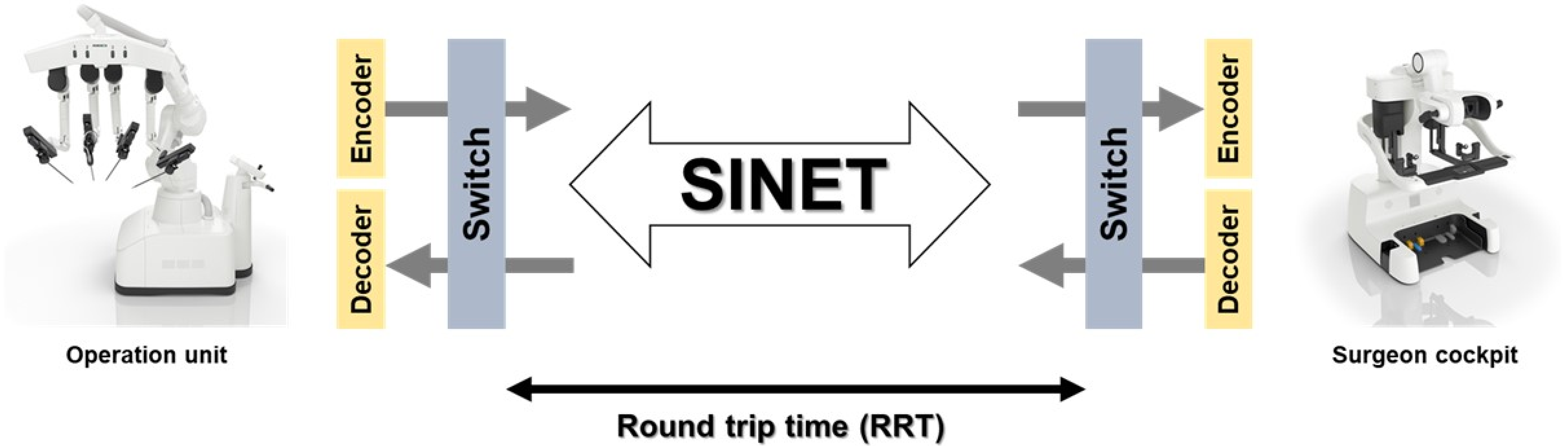
The total amount of communication data (including the robot control signal) was 130–155 Mbps at video compression (VC) 1 (120 Mbps), 50–65 Mbps at VC 2 (40 Mbps), 35–40 Mbps at VC 3 (20 Mbps)

Fig. 7 Intracorporeal suturing completion time, and the robotic skill evaluation using the Global Evaluative Assessment of Robotic Skills (GEARS), and the subjective evaluation of the surgeon was validated using the System and Piper Fatigue Scale-12 (PFS-12)

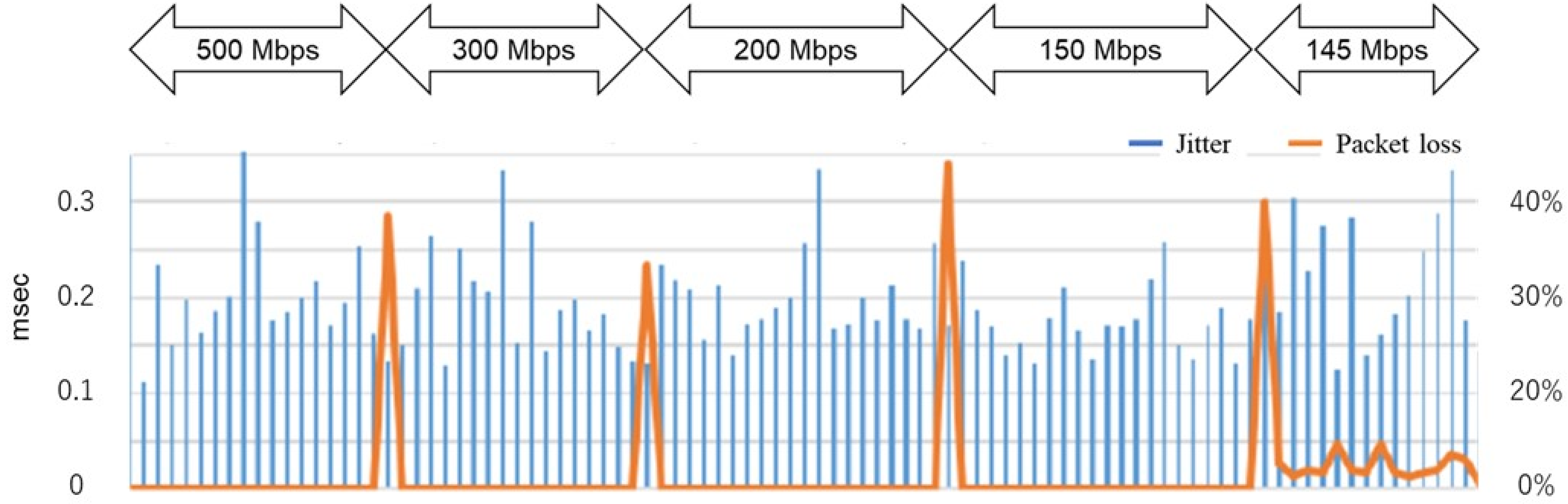
a. Intracorporeal suturing completion time: VC1 significantly prolonged the task completion time compared to that with VC2 and VC3 (P= 0.009 and P=0.009, respectively). b. GEARS scores with VC1 were significantly lower than those with VC2 and VC3 (P=0.008 and P=0.009, respectively). c. PFS-12 scores with VC1 were significantly higher than those with VC2 and VC3 (P= 0.009 and P=0.009, respectively).

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


SINET
HUH
KUH
2000km



Encoder
Decoder
Switch
SINET
Switch
Encoder
Decoder
Operation unit
Surgeon cockpit
Round trip time (RRT)


500 Mbps
300 Mbps
200 Mbps
150 Mbps
145 Mbps
Jitter
Packet loss
msec
0.3
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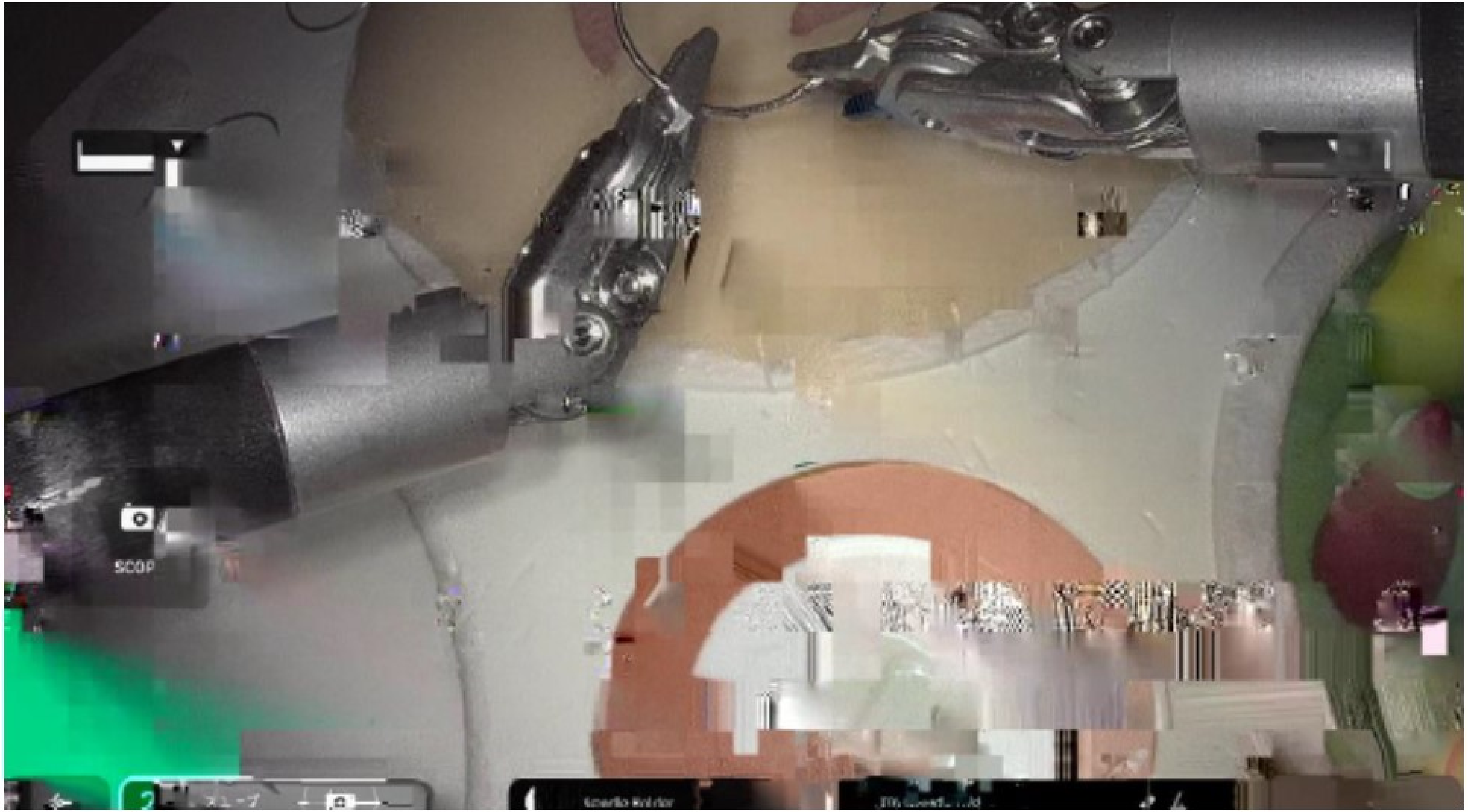
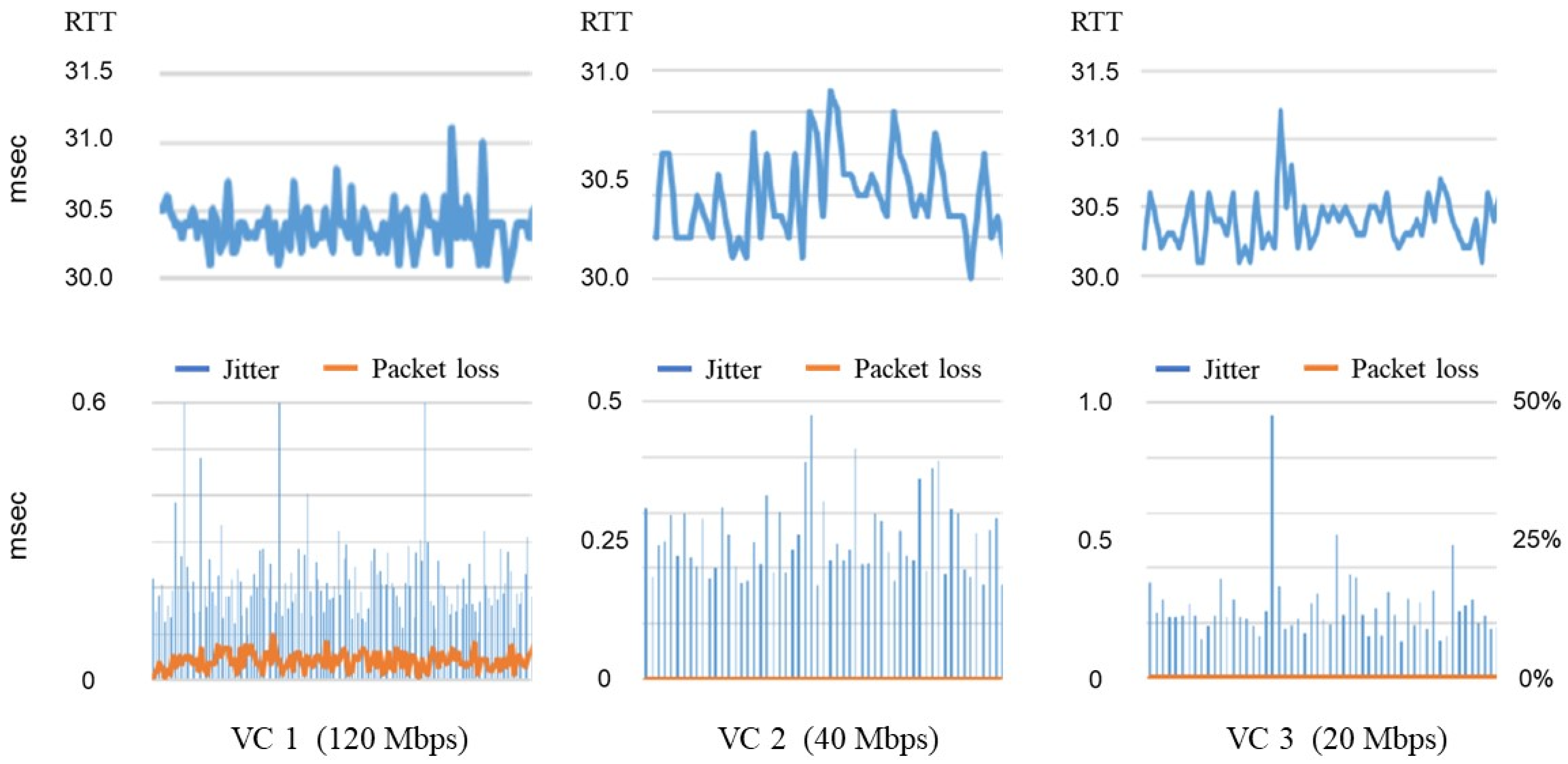
30%
20%
0%

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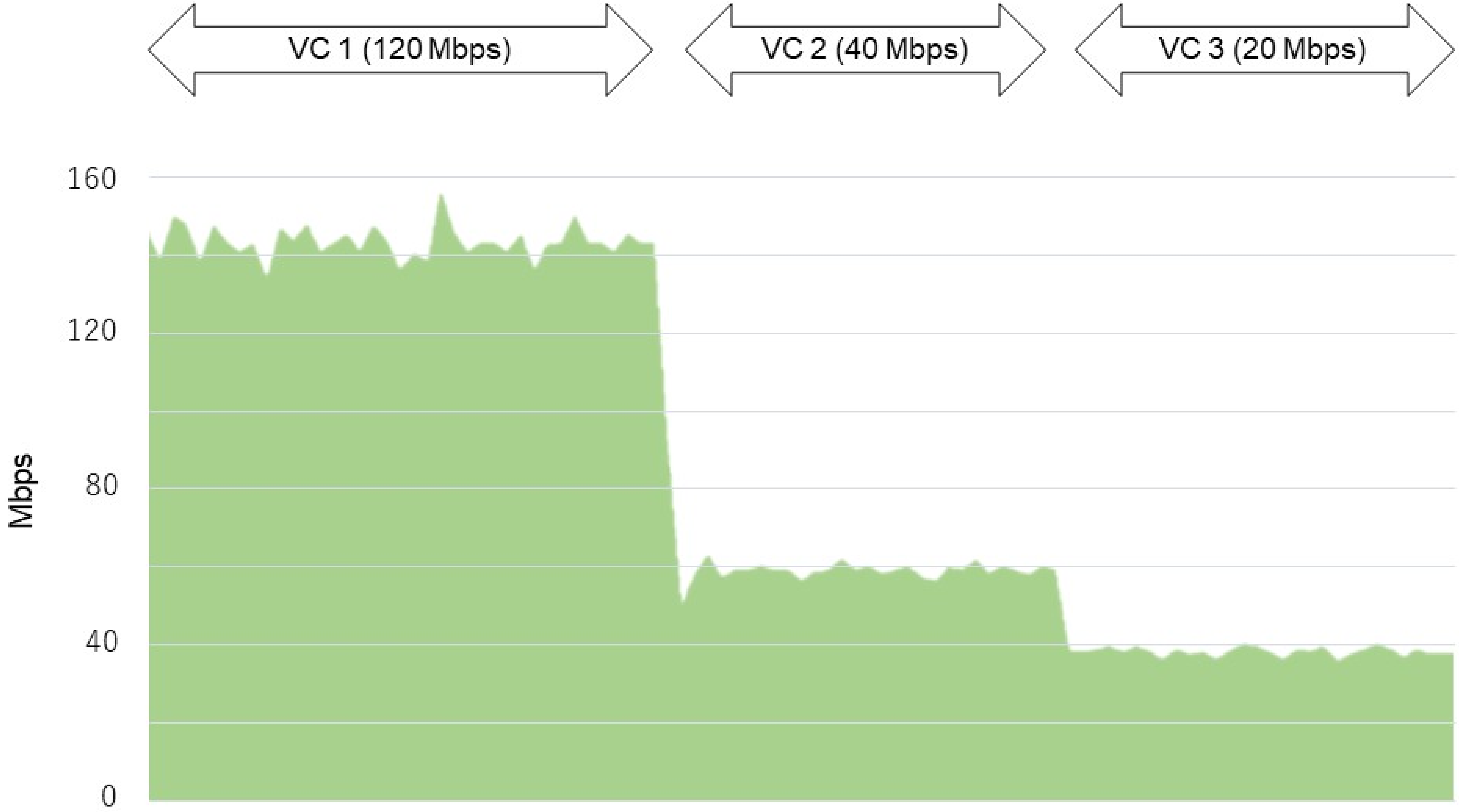
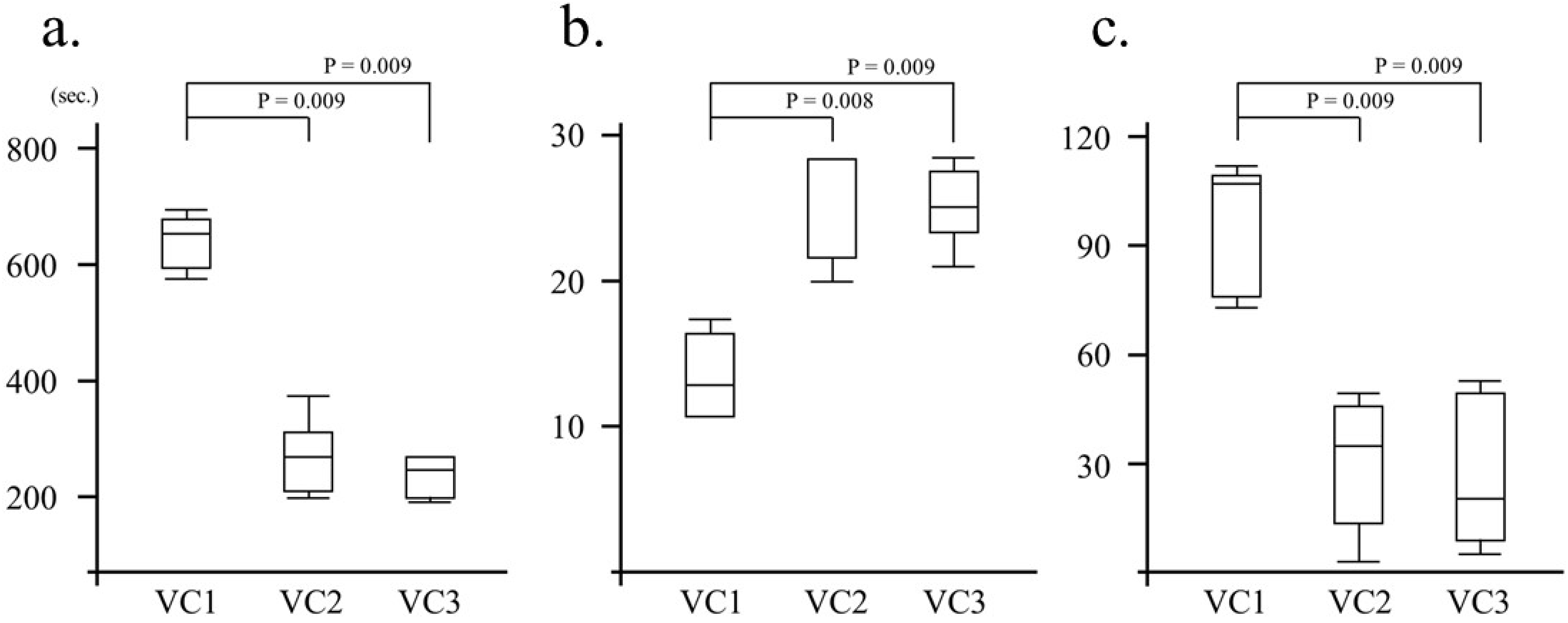
msec
Jitter
Packet loss
0.5
0.25
0
Jitter
Packet loss
1.0
0.5
0
50%
25%
0%
VC 1 (120 Mbps)
VC 2 (40 Mbps)
VC 3 (20 Mbps)



VC 1 (120 Mbps)
VC 2 (40 Mbps)
VC 3 (20 Mbps)
160
120
80
40
0
Mbps


a.
(sec.)
P = 0.009
P = 0.009
800
600
400
200
VC1
VC2
VC3
b.
P = 0.009
P = 0.008
30
20
10
VC1
VC2
VC3
c.
P = 0.009
P = 0.009
120
90
60
30
VC1
VC2
VC3