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5G Remote Robot-Assisted Hepatobiliary and Pancreatic Surgery: A Report of Five Cases and a Literature Review

Yuxin Fan[1] | Chao Ma[1] | Xinyu Wu[1] | Tianyong Cai[1] | Xiao Liang[2] | Zheyong Li[1,2] | Xiujun Cai[2]

[1]Sir Run Run Shaw Hospital, Alaer Hospital, Zhejiang University School of Medicine, Hangzhou, China | [2]Sir Run Run Shaw Hospital, Zhejiang University School of Medicine, Hangzhou, China

Correspondence: Zheyong Li (lizysrrsh@zju.edu.cn) | Xiujun Cai (srrsh_cxj@zju.edu.cn)

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ABSTRACT

Background: This study aimed to explore the feasibility and safety of using 5G communication technology for domestic surgical robots to perform ultra-remote hepatobiliary and pancreatic surgery.

Methods: A retrospective analysis was conducted on the clinical data of five cases of ultra-remote domestic robot-assisted laparoscopic hepatobiliary and pancreatic surgery completed at Sir Run Run Shaw Hospital, Zhejiang University School of Medicine (referred to as Hangzhou, Zhejiang) and Sir Run Run Shaw Hospital, Alaer Hospital, Zhejiang University School of Medicine (referred to as Alaer city, Xinjiang) from February to September 2023. The main system of the operating desk at Hangzhou, Zhejiang, uses 5G network signal transmission to remotely control the bedside operating system at Alaer City, Xinjiang. The physical distance between the two locations is 4670.2 km, and the network communication distance is 5031.2 km. The operators and assistants are immobilised.

Results: The operations were successful. The number of network image frames was 50, the median delay was 73 (70.25–126.1) ms, and the median operation time was 39 (31–128) min. The median intraoperative blood loss was 2 (2–30) mL. No occurrence of network disruption or data packet loss was observed. One case of instrument adverse event occurred, and the patient returned to normal after replacement. The median times taken to get out of bed, ventilation, and hospitalisation were 19 (15–46) h, 2 (2–4) d, and 3 (3–13) d, respectively. According to the Clavien–Dindo classification, the postoperative complications in one patient were Grade I; no other surgical complications were observed. No abnormalities were observed in the patients after a 30-day re-examination. All patients successfully recovered after a 2-month follow-up.

Conclusions: It is safe and feasible for domestic robots to perform 5G remote robot-assisted hepatobiliary and pancreatic surgery.

1 | Introduction

Advancements in modern medical science and clinical practice have promoted the understanding of hepatobiliary and pancreatic diseases. The rapid development of modern imaging technology, improvements in anaesthesia medicine, and iterative updates to surgical instruments have enhanced our understanding of the molecular mechanisms and microscopic anatomy of diseases. Hepatobiliary and pancreatic surgeries include open surgery, minimally invasive laparoscopic surgery, and robot-assisted

minimally invasive laparoscopic surgery. With the introduction of high-tech technologies, such as big data, artificial intelligence, surgical robots, 5G network communication technology, and satellite communication in the surgical field, hepatobiliary and pancreatic surgery has entered the surgical 4.0 era [1]. Previously, robotic hepatobiliary and pancreatic surgery was frequently performed in large medical centres and rarely applied in remote primary medical units. With the novel application of 5G technology in multiple fields, the current study took advantage of the opportunity to construct national regional medical centres. In Xinjiang, which is a small northwestern border town, and Hangzhou and Zhejiang, which are located on the East China Sea coast, remote hepatobiliary and pancreatic surgeries have been conducted to achieve this goal. From February to September 2023, the research team used the Toumai four-arm robot of the domestic Shanghai MicroPort MedBot (Group) Co., Ltd. To customise a 5G network of China Telecom. Five cases of ultra-remote hepatobiliary and pancreatic surgeries were completed with favourable outcomes. After completing the world's first 5G ultra-remote robot-assisted cholecystectomy [2], we developed the world's first 5G remote robot-assisted liver resection [3]. No reports exist on the use of 5G technology to conduct remote robot-assisted hepatobiliary and pancreatic surgery, especially for a network communication distance that exceeds 5000 km either domestically or abroad. This study analysed the clinical data from five patients and 5G network communication data to explore the feasibility and safety of remote hepatobiliary and pancreatic surgery using a 5G technology domestic surgical robot.

2 | Materials and Methods

2.1 | General Information

The patients who underwent robotic surgery fulfiled the following criteria: they had surgical indications for hepatobiliary and pancreatic surgery. We performed robot-assisted laparoscopic hepatobiliary and pancreatic surgery, and the patients were followed up for more than 3 months. The patient characteristics were as follows: age, 35–46 years; body mass index (BMI), 23.4–25.8 kg/m^2; American Society of Anaesthesiologists (ASA) grade I–II; no serious cardiopulmonary disease observed during preoperative examination; ability to tolerate surgery; willingness to sign the consent form; and willingness to follow the doctor's instructions. Regular follow-up can be observed as ordered by the doctor.

All patients underwent surgery at the Department of General Surgery, Alaer city, xinjiang. The doctor at the remote end was Professor Xiao Liang, General Surgery, Hangzhou, Zhejiang. The physical distance between the two locations is 4670.2 km, and the network transmission distance is 5031.2 km. Five patients, including two men and three women, were included in this study. The median age was 43 (35–46) years, and the median BMI was 24.1 (23.4–25.8) kg/m^2. Four and one patient had ASA grades of 1 and 2, respectively. Cholecystectomy was performed in three patients, hepatic haemangioma resection was performed in one patient, and spleen-preserving distal pancreatectomy was performed in one patient.

Professor Xiao Liang and his team from the Department of General Surgery at the same institution performed all five ultra-remote robot-assisted laparoscopic surgeries. Both the primary surgeon and assisting physicians had over 10 years of experience in laparoscopic procedures, with more than 100 robotic surgeries completed. Prior to the surgeries, the team was certified to operate the Toumai endoscopic system, conducted more than 20 animal surgeries, and underwent simulation training in remote robotic operations.

2.2 | Robots and Networks

In this study, five cases of 5G ultra-remote surgery were completely autonomous and performed using the Shanghai MicroPort MedBot (Group) Co., Ltd. A Toumai four-arm robot (Thoracic and Abdominal Endoscopic Surgery System, Model: MT-1000), which was developed and registered before the project was conducted (National instrument registration number: 20223010108), was used. The surgical robot system comprises three parts: the doctor's console, including the remote doctor's console (the main system) and the local doctor's console (to take charge of the surgery in case of network failure); the image platform, and the patient's surgery platform (the slave system). The remote doctor console was located in Hangzhou, Zhejiang, and the local doctor console, image platform, and patient surgery platform were located in the operating room of Alaer city, Xinjiang. The 3D electronic endoscope collects the stereoscopic image information of the surgical field in real time, enlarges it by 10 times, and transmits it to the 3D monitor of the surgeon's console via the 5G network. The surgeon views lesions and surgical instruments within the patient's body via a stereoscopic monitor and controls these instruments through a main control arm, which captures the surgeon's wrist movements. These signals are transmitted to the surgical tools and 3D electronic endoscopes on the operating platform. This setup provides real-time surgical views for assistants and nurses, ensuring smooth operations under a 5G network from China Telecom. For safety, a dedicated fibre network backs up the 5G signal to handle potential failures. Additionally, a local doctor console allows immediate takeover in the case of unresolvable network issues, preventing surgical mishaps. Throughout the surgery, network delay, fluctuation, and packet loss are monitored to assess network stability.

2.3 | Surgical Process

The robotic surgical system engineers tested the robotic system operation and network environment before surgery. Tracheal intubation and general anaesthesia were used in all five patients. After successful anaesthesia, the surgical assistant team placed the patient in position, disinfected the cloth, and laid the holes. According to the surgical requirements, 4–5 trocars were set up for puncture, and the surgical engineer team started the equipment and moved the surgical platform to the appropriate position. The surgical team placed an aseptic protective cover on the robotic arm and connected it to the trocar. The surgical instruments were subsequently placed into

the trocar and connected to the robotic arm to complete the installation. The robot operation is completed by the surgeon operating the robot arm through the ultra-remote-control console, and the local surgical assistant is assisted by the suction device to attract, insert, or remove the gauze; the suture is inserted to remove the suture needle; and the blood vessel and bile duct are clamped. Following the removal of the pathological tissue, the surgeon filled the specimen bag, the assistant removed the specimen, cleaned the operative area, removed the trocar, and sutured the incision, thereby completing the surgery, after which the operating platform was evacuated (the operation picture can be seen in Figure 1).

2.4 | Evaluation Methods

The main objective of this study was to evaluate the success of ultra-remote surgery without obvious iatrogenic injury or intraoperative complications. The surgery was successful if the diseased tissue was successfully removed without being transferred to other surgical methods. However, if remote robot surgery was transferred to local robotic or laparoscopic surgery because of network issues, remote surgery was considered a failure [4].

Other evaluation indicators included network delay time (collecting surgical information from the bedside patient's operating platform to the surgeon's console, operating instructions from the surgeon to the operating platform to execute the instructions for the robotic arm to complete the surgery), the number of data packet loss cases, the resection time of lesion tissue (the robot is successfully installed to the bedside operating platform to withdraw the machine), the amount of intraoperative blood loss, network loss, an adverse event of the instrument, the time taken to get out of bed following surgery, surgical complications, and postoperative 30-day re-examination.

3 | Results

Five ultra-remote robot-assisted hepatobiliary and pancreatic surgeries were successfully performed, establishing a world record. The network maintained a stable image frame rate with a median delay of 73 ms and experienced no disruptions or packet loss. The surgeries varied in duration: median cholecystectomy time 38 (31–128) min, resection of the hepatic angioma 49 min, and resection of the pancreatic body and tail tumours preserving the spleen 128 min; median time was 39 min overall. The median blood loss was 2 mL. An issue with an ultrasonic knife was resolved by replacing the head and reconnecting the arm. The patients' median recovery times were as follows: getting out of bed (19 h), exhaustion after surgery (2 days), and hospital discharge (3 days). Postoperative pain was effectively managed with analgesics, and no serious surgical complications occurred [5]. Follow-up at 30 days revealed no abnormalities, and all patients recovered within 2 months (detailed data are shown in Table 1).

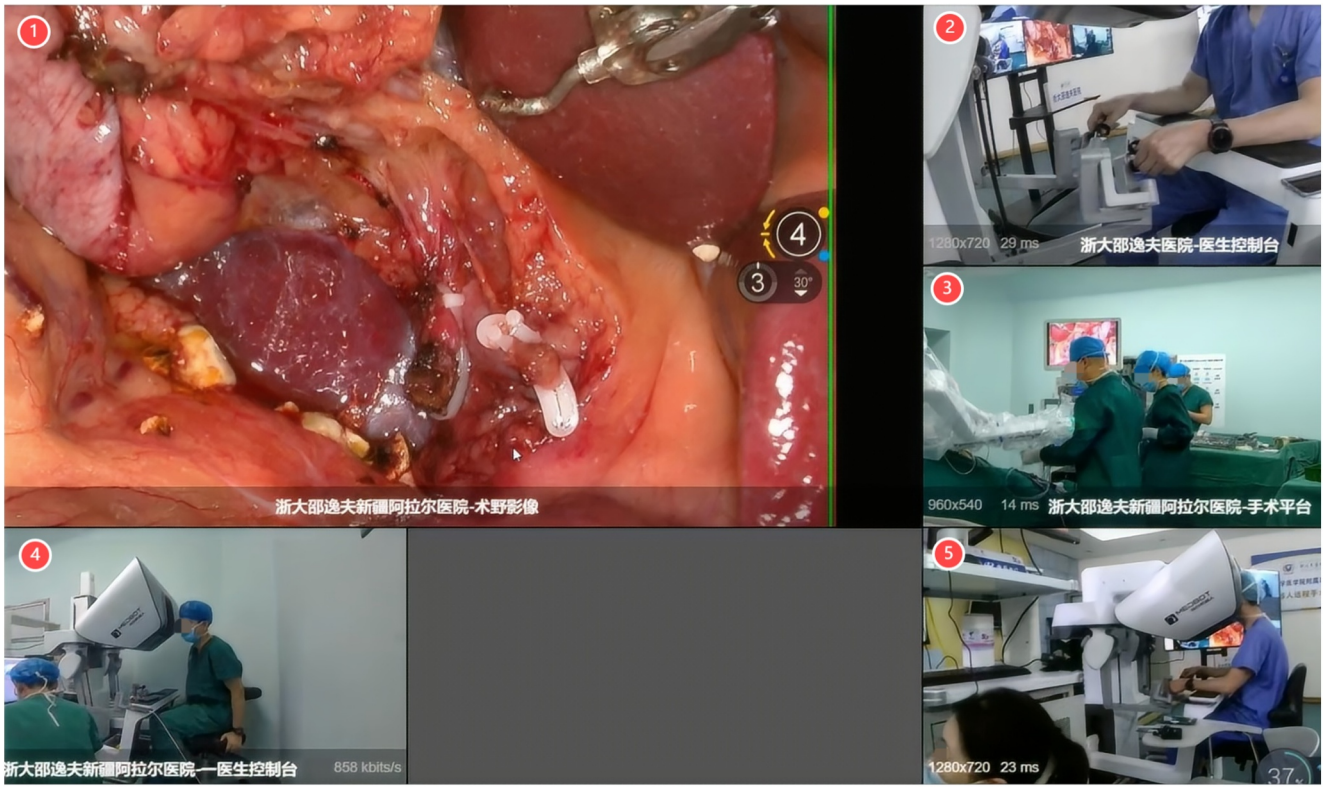

FIGURE 1 | ① Surgical field of view. ② The surgeon controls the main operating system to perform surgery in Hangzhou, China. ③ Operating room scene in Alaer City, Xinjiang, China. ④ The standby surgeon at the operation site is ready to take over the operation at any time to prevent surgical accidents when network accidents occur. ⑤ The surgeon's remote operating table environment.

TABLE 1 | Data of the patients.

Number	Mode of operations	Age (year)	Sex	BMI (kg/m^2)	ASA grade	Average network latency (ms)	Time of surgery (min)	Intraoperative bleeding (mL)	Adverse event	Getting out of bed time (hour)	Exhaust time after surgery (day)	Postoperative length of hospital stay (day)	Grade of postoperative complications
Case 1	Cholecystectomy	46	Male	24.4	I	/	39	2	—	15	2	3	—
Case 2	Cholecystectomy	35	Female	24.1	I	125.63	38	2	—	17	2	3	—
Case 3	Cholecystectomy	43	Female	25.8	II	126.10	31	2	—	19	2	3	—
Case 4	Resection of the hepatic angioma	36	Female	23.8	I	73	49	30	—	36	2	6	—
Case 5	Spleen preserving distal pancreatectomy	43	Male	23.4	I	70.25	128	30	1	46	4	13	I
Median value		43	—	24.1	—	73	39	2	—	19	2	3	—

4 | Discussion

The research and application of telemedicine devices originated in the mid-20th century, but owing to limitations in the development of key technologies such as communication network conditions and hardware, the application of telemedicine devices continues to be in the primary stage of remote consultation and teaching. The progress and popularisation of internet technology have broken the spatial limitations of interpersonal communication and realized cross-regional exchanges and communication. Since the birth of internet technology, the medical community has started using it to overcome the limitations of time and space. In September 2001, doctors from New York attempted the world's first remote surgery in patients from Trasbourg, which is located on the other side of the Atlantic [6]. Using the ZEUS robotic system, which transmits signals via a dedicated undersea optical fibre, the patient underwent a cholecystectomy, known as the "Lindbergh" operation. Irrespective of the technical limitations during that time, the most advanced network technology was used; however, the network delay in animal tests was still as high as 155 ms, and the physical connection through optical fibres was costly, thereby limiting its promotion [7]. As this network delay is unacceptable for delicate surgeries, scientists have continuously challenged remote surgery with technological breakthroughs on the internet. In 2016, China's domestic surgical robot S [8] completed remote gallbladder removal, gastric perforation repair, and liver wedge resection in pigs in Tianjin, which is 118 km away from Beijing, and it is considered the first successful case of remote abdominal surgery in animals in China. The operation times were 50, 20, and 30 min, and the blood loss volumes were 5, 0, and 15 mL, respectively. In 2018, Kondo Robot [9] successfully completed wedge resection of pig liver in Fuzhou at a distance of 50 km. The average intraoperative delay was < 150 ms, the operative time was 60 min, and the volume of bleeding was about 5 mL. In September 2020, Haitao et al. from the Affiliated Hospital of Qingdao University used a 5G wireless network to perform four ultra-remote laparoscopic surgeries in animal experiments [10], including robot-assisted laparoscopic left nephrectomy, partial hepatectomy, cholecystectomy, and cystectomy. The average network latency was 264 ms, including an average round-trip transmission delay of 114 ms and a packet loss rate of 1.20%. The total operation time was 2 h, and the total blood loss volume was 25 mL, with no intraoperative complications. The preliminary results proved that remote surgery could be safely and smoothly conducted with the support of a 5G wireless network, even for ultralong distances. In 2021, the Kangdo Surgical Robot [11], equipped with a 5G network, successfully completed three cases of remote domestic robot-assisted laparoscopic non-functional nephrotomy at the Affiliated Hospital of Qingdao University (network communication distances of 82.5, 141.0, and 229.0 km, respectively), with an average intraoperative delay of 27.3 ms and no network packet loss. The average total delay time, operation time, and estimated intraoperative blood loss were 177.3 ms, 79.3 min, and 31.1 mL, respectively. In this study, the network transmission distance for the five cases of 5G ultra-remote robot-assisted hepatobiliary and pancreatic surgery was much greater than that reported in previous studies, verifying the feasibility of ultra-remote robotic surgery.

Telemedicine is a key future strategy in China, addressing the imbalance in medical resource distribution with developments such as remote diagnosis, mobile wards, and digital operating rooms. Remote surgery, although still nascent, offers significant benefits by optimising medical resources, reducing treatment costs, and enhancing efficiency, ultimately improving patient convenience. It can also provide surgery and high-quality medical services for special emergencies such as disaster areas, battlefields, and even space [1]. The commercialisation of the 5G network is a symbol of the modernisation of remote surgery in China, and its characteristics of low delay, high bandwidth, and high mobility can meet the needs of real-time, efficient, and stable remote surgery, thereby promoting a research boom in remote surgery in China. When a 5G communication network is used as a medical information transmission carrier, new telemedicine models that integrate robots, virtual reality, and artificial intelligence technology with remote diagnosis, guidance, and operation and evaluation of medical surgery are crucial and challenging aspects of telemedicine. It can effectively address challenges in medicine, such as unbalanced medical resources, laborious surgeries, and costly medical treatment [12].

The hospital is located in the northwestern border area of China, where basic medical facilities are underdeveloped compared with those in eastern coastal cities. However, given the rapid development and promotion of 5G mobile communication network technology in China and the implementation of the national policy of the 'Healthy China 2030' plan, people residing in border areas can benefit from 5G remote robotic surgery. Previously, many practices at home and abroad have proven that a remote robot has unique advantages in urological surgery, but few studies have explored its utilization in general surgery, especially in hepatobiliary and pancreatic surgery. Run Run Shaw Hospital of Zhejiang University and our hospital successfully completed five cases of ultra-remote 5G remote robot hepatobiliary and pancreatic surgery, which verified the operability of domestic robots in the application of hepatobiliary and pancreatic surgery. The key elements of successful surgery include the following: experienced robot surgery operators for smooth functioning, safe and reliable surgical robots, and high-speed and stable network transmission. With clear and stable surgical field imaging in the five cases, immediate and error-free transmission of operation instructions, operator adaptation to network delay, and accurate completion of the surgery, the preliminary results verified the safety and reliability of domestic robots at an ultralong distance of more than 5000 km with a 5G wireless network in hepatobiliary and pancreatic surgery.

The key to the success of remote surgery is the consistency and real-time operation of the master and slave systems in the surgical robot, followed by the resolution of technical problems such as signal stability, anti-interference, and high-throughput signal transmission [9]. The key to ensuring the efficient completion of remote surgery is the data transmission speed. Network and data transmission delays seriously impact the surgical operation and operation time, respectively, and the change in delay with time is prone to the disorder of data packets, resulting in the movement of the robot operator's jitter. Currently, numerous studies conducted on remote surgery at home and abroad generally believe that the standard of network selection in the ideal state for remote surgery is a total network delay < 200 ms, but the successful completion of surgery will be unaffected within 300 ms; however, a greater network delay will affect the safety and accuracy of surgery, and thus, the surgery cannot be performed [13]. In this study, a domestic Toumai four-arm robot and the 5G network of China Telecom were used. The robotic arm movement of the surgical robot was flexible and smooth, and the median network delay was 73 (70.25–126.10) ms, which ensured smooth implementation of the surgery. One adverse event that occurred in this study was the inability of the ultrasonic knife to bite and cut the tissue normally. Despite removing and wiping the ultrasonic knife head, it was unable to function normally. After it was replaced with a new ultrasonic knife head and the mechanical arm was reconnected, its function was restored. Although the problem is short in duration and simple in resolution, it affects the flow of the surgery, thereby showing that the domestic surgical robot needs further improvement concerning the consumables of the robotic arm.

Five cases of ultra-remote robotic hepatobiliary and pancreatic surgery were performed by the same surgical operator and on-stage assistants. The surgeon was highly experienced in minimally invasive hepatobiliary and pancreatic surgery, and China has been leading in the volume of robotic operations conducted, compensating for interference such as network delay and robot coordination. In addition, all five cases were handled by local physicians with considerable experience in robotic hepatobiliary and pancreatic surgery in the secondary operating room in case of emergencies.

In summary, all five cases of ultra-remote robot-assisted hepatobiliary and pancreatic surgery were successfully completed. No network adverse events occurred during the surgery. One case of adverse events occurred in surgical robot accessories, which were immediately resolved with no postoperative complications, verifying that with the support of the 5G network of China Telecom, it was safe and feasible to perform ultra-remote hepatobiliary and pancreatic surgery utilising the Toumai thoracic and abdominal endoscopic surgery system. This is a preliminary exploratory study on the application of a domestic robot in ultra-remote surgery using a 5G network. Further verification should be conducted via national registered clinical trials. The limitations of this study include the small sample size, limited disease types, and short follow-up time. The presence of diverse indications and surgical techniques contributes to the observed heterogeneity. Future multicenter studies with large sample sizes are needed to confirm the observations of this study and draw further scientific conclusions.

Author Contribution

Yuxin Fan: data curation, formal analysis, investigation, validation, visualisation, writing–original draft preparation. **Chao Ma:** data curation, investigation, resources, validation. **Xinyu Wu:** data curation, formal analysis, investigation, resources. **Tianyong Cai:** supervision. **Xiao Liang:** methodology, project administration, resources, supervision, validation, visualisation. **Zheyong Li:** conceptualisation, funding acquisition, methodology project administration, resources, supervision, writing–review & editing. **Xiujun Cai:** conceptualisation, funding acquisition, project administration, writing–review & editing.

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Ethics Statement

The study was approved by the ethics review board of Sir Run Run Shaw Hospital, Alaer Hospital, Zhejiang University School of Medicine (No. 2022-001) in accordance with the Declaration of Helsinki. Written informed consent was obtained from all individual patients included in the study.

Consent

The authors have nothing to report.

Conflicts of Interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. All authors disclose no relevant relationships.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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