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REVIEW ARTICLE

Application of 5G telesurgery in urology

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Abstract
The fifth generation of mobile communication technology (5G technology) features large system capacity, fast data transmission rate, support for large-scale device connection, low latency, and high reliability. With the development and popularization of 5G technology, it is also widely used in medicine. In recent years, 5G telesurgery has been paid attention to and made continuous progress, and the research related to its combination with urology has also made significant achievements. We collect the combination of 5G technology and urology improves the uneven distribution of medical resources, provides timely, high-quality remote surgical interventions for urology patients, reduces the financial burden on patients, surgical complications, and the difficulty of accessing medical care from a distance, and brings new opportunities for medical development.

KEYWORDS
5G, application, robot, telesurgery, urology

1 | INTRODUCTION

Telesurgery is a newly developed surgical mode in recent years. The core of telesurgery includes the network communication connecting patients, surgeons and the robotic system used for surgical operations. Theoretically, the model mitigates significant medical burden disparities, potential treatment complications, and other problems due to differences in the geographic distribution of medical resources. Telesurgery not only benefits patients but also provides technical accuracy in surgical operations, avoiding the potential risk of intraoperative exposure due to surgeon error that can occur in traditional surgical models, and ensuring surgeon safety[1]. However, there are still some limitations in the current research of telesurgery, the most important problem is that the communication technology cannot ensure that the network latency is maintained at an acceptable level. Latency is the time it takes for data to travel from one terminal to another. It is a result of the limited speed of information transmission. There is no doubt that excessive latency is a huge obstacle to carry out telesurgery, and greatly affects the development and popularization of telesurgery mode. The fifth generation (5G) network communication technology with a fast transmission rate and low latency can meet the requirements of real-time, high efficiency and stability of telesurgery. In recent years, with the popularity of 5G technology, many studies at home and abroad have started to try to apply 5G technology to remote surgery in urology and other disciplines, and a series of results have been achieved, showing us the great development potential of 5G telesurgery in the field of surgery and the new direction of future surgical technology development.

2 | DEVELOPMENT HISTORY OF TELESURGERY

With the first-mover advantage in Internet technology, European and American countries explored the field of telesurgery as early as the 1990s. Since the 1990s, telemedicine in the surgical field has developed rapidly.

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The first real-time teleconsultation on telesurgery was reported in 1992[2]. It was about a standard telephone network used for teleconsultation of pathology slides during surgery, but due to the limitations of the network technology and the medical level at that time, only 37% of the 35 cases were accurate. In the same year, Satava et al.[3] used SRI remote operating system to directly control the movement of the mechanical tip to complete part of the operation. Based on this operating system, they developed the currently widely used Da Vinci robotic system[4], which was the beginning of the telesurgery robot and the turning point of telesurgery from the field to the remote operation. In 1999, a surgeon performed a laparoscopic gastric banding procedure at a distance[5]. The surgeon manipulated handles that were connected to a computer in command of robotic arms mounted on the operating table near the patient. The successful completion of the operation proved the possibility of telesurgery.

With the continuous exploration of this field, telesurgery also developed from the initial simple remote operation to a more systematic telesurgery mode. In 2001, the "Charles Lindbergh surgery" was completed[6]. The patient receiving the surgery was a 68-year-old female patient with gallstones in Strasbourg, France. The surgeon performed the operation in New York, 7000 km away. This was a milestone of telesurgery and verified the feasibility of telesurgery. However, it also revealed many problems, such as the huge cost of laying a special submarine cable in the preliminary preparation, the excessive expenditure of manpower and material resources, and the long preparation period. Since then, due to the limitation of communication technology, the problem of network latency had never been effectively solved, making the development of telesurgery slow.

The exploration of telesurgery in urology can be traced back to 1994, when some scholars carried out telesurgery guidance in Maryland, USA[7]. A remote site was set up at the hospital where the operating room was located, the patient and the surgeon were 1609 km apart, all components in the surgery were connected to a signal source in the operating room, a device was added to the surgical system to control cutting and hemostasis, and 32 simple surgical operations were completed using this initial telesurgery system, but the problem of data transmission between the two terminals of the patient and the surgeon was not solved, which is the key problem in the development of telesurgery.

To solve this critical problem, Moore et al.[8] tried to perform the basic operations of seven telesurgeries in 1996. Applying a LAN network line with a bandwidth of 1.5 Mb/s to perform intraoperative operations such as cutting and hemostasis at a site approximately 5.6 km away, and performing intraoperative audio, video, operating instructions and necessary data transmission, and several key features of remote surgery were identified in this study, namely, high-quality audio and video transmission.

Based on the above study, Lee et al.[9] attempted to perform long-distance transcontinental laparoscopic robotic surgery across continents in 1998. They guided young physicians about 8047, 14 484, and 17 703 km away to perform different urological operations with a network latency of about 1 s and a bandwidth of about 384 kb/s. Despite the limitations in this study such as geographical location and limited level of network technology, the procedures were all completed successfully with remote guidance. In 1998, the team used the same network technology to perform a percutaneous renal puncture in Italy, 7242 km away, with a specially developed robotic system that completed the kidney puncture in an average of 20 min[10].

In 2001, Abbou and colleagues[11] attempted a telerobotically assisted laparoscopic radical prostatectomy. A 63-year-old patient with a Gleason score of 3+3 for prostate cancer was successfully operated on by a surgeon via the Da Vinci Robotic Surgical System telemanipulators in another location. The operation was completed in approximately 420 min. The blood loss was 300 mL, and the patient was discharged from the hospital successfully 4 days later and was fully continent 1 week later. This was the first reported case of a telerobotically assisted laparoscopic radical prostatectomy, further verifying the feasibility of telesurgery in urology, but the experiment also exposed some problems, such as lack of tactile feedback and high cost of surgical equipment. It was important to note that the term telesurgery here referred to a surgeon performing surgery from a location other than the operating table, but not far from each other, such as the Da Vinci Surgical Robotic System.

Compared with foreign countries, domestic telemedicine started relatively late, but the rapid development of telemedicine had been explored to match our national conditions. In the field of ultraremote surgery, multidisciplinary teams combined telesurgery, and so on, we had made a leapfrog breakthrough. The commercialization of the 5G network was a sign of the modernization of telesurgery. Its characteristics of low latency, high bandwidth, and high mobility can meet the demands of real-time, high efficiency and stability of telesurgery. The related research on the combination of the 5G network and medicine had been making progress in recent years. In the field of urology, many domestic urology teams had made many advances in the field of urology 5G telesurgery, providing important support for the development of 5G telesurgery[12].

3 | RESEARCH PROGRESS OF 5G TELESURGERY

3.1 | 5G network for telesurgery

The development of telesurgery needs a supporting remote network system. According to statistics, the maximum total latency acceptable to physicians for the operation of the robotic surgery system is 330 ms, and considering the robot's performance and surgical operation factors, a total latency of less than 300 ms is the ideal state for the smooth development of telesurgery. In 2007, Nguan et al.[13] performed robot-assisted laparoscopic pyeloplasty on female pigs with a latency of 510 ms, which was relatively large and could not meet the needs of telesurgery.

Since 2019, many foreign studies have tried to apply the 5G network to telesurgery and obtained satisfactory results. Lacy et al.[14] applied the 5G network to provide remote surgical guidance to patient-side young doctors. Although the operation was carried out smoothly, the potential of the 5G network in this field was not fully developed. On this basis, Acemoglu et al.[15] reported that they applied the 5G network to perform a robotic vocal cord operation on a corpse in an autopsy laboratory 15 km away, and finally, the operation was successfully completed with an average network latency of 140 ms. This study showed that the characteristics of the 5G network, such as low latency and high bandwidth, were key technologies for telesurgery.

3.2 | Robotic surgical system for telesurgery

The stability of robotic surgical systems is one of the important factors for the success of telesurgery. In terms of robotic surgery systems, the degree of freedom and stability of the manipulator should be maximized to reduce delays and data loss during information processing to meet the requirements of remote surgery on the complexity, accuracy, and stability of the manipulator arm operation. Among the robotic surgical systems currently in use, the Zeus robotic surgical system, the earliest one put into use, has a lower degree of freedom of the robot arm and can complete relatively simple remote operations[16]; however, the more widely used Da Vinci Robotic Surgical System has seven degrees of freedom in its robotic arm, theoretically allowing for more complex remote operations[17].

Compared with foreign countries, a number of studies have proved the feasibility and safety of domestic surgical robot systems applied in telesurgery[18], such as based on its seven degrees of freedom, the domestic MicroHand robotic surgery system with independent intellectual property rights adopts the control strategy of decoupling design of instruments and dial-and-cure of position and pose, which reduces the number of linked joints in telesurgery and improves the synergy, precision, and stability of the master–slave operation of the remote robotic surgery system to a greater extent. The self-developed KangDuo Surgical Robot-01 (KD-SR-01) system, creatively set up with a dual console system, can guarantee that the surgery will not be interrupted in case of communication failure, thus ensuring the safety of the surgery, while being able to eliminate the barriers of time and location, enabling cross-distance cooperation for challenging cases and real-time assistance.

3.3 | Surgical team for telesurgery

Compared with traditional robotic surgery, telesurgery is operationally different. Because of the lack of direct contact with patients, it is difficult to obtain comprehensive surgical information in a timely manner, and the operator often needs to overcome the influence of more mental and psychological factors, plus the potential impact of network latency on the surgical process, so before performing telesurgery, the surgeon needs to receive a lot of simulation training, as well as timely assessment and intervention of the surgeon's psychological state. In 2014, Xu et al.[19] proposed a simulation scheme for the remote operation of surgeons. However, since then, relevant research on remote operation specifications of surgeons has stalled, which has become a problem to be solved in the development of telesurgery.

4 | APPLICATION OF 5G TELESURGERY IN UROLOGY

4.1 | Application of 5G telesurgery in bladder surgery

The application of 5G telesurgery in bladder surgery had not been reported for a long time. In 2020, Niu and colleagues[18] performed a 5G laparoscopic telecystectomy, on a pig model with a network connection distance of more than 3000 km. During the experiment, the team used the domestic MicroHand surgical robot for surgical operation, and all four cases were successfully and safely completed. The results showed that the average network latency was 264 ms (the average round-trip transmission latency was 114 ms, the packet loss rate was 1.20%), the operation time was 2 h, the intraoperative blood loss was 25 mL, and no complications occurred. The safety and feasibility of 5G telesurgery in bladder surgery were preliminarily verified in animal models.

In September 2020, Niu and colleagues[20] successfully performed a telesurgical robot-assisted laparoscopic radical cystectomy spanning nearly 3000 km. During the operation, the surgeon successfully completed the standard operating procedures. The operation time was about 5 h, and the intraoperative blood loss was about 200 mL. No intraoperative complications occurred, and the patient recovered smoothly after the operation. The average round-trip delay of this telesurgery was 104 ms, and the packet loss rate was 0%.

This is the world's first report of 5G ultraremote radical cystectomy, which has had an important impact on the further promotion and development of telesurgery.

4.2 | Application of 5G telesurgery in renal surgery

Telesurgery has been applied to kidney surgery since the 1990s, but the combination of 5G telesurgery and kidney surgery is rarely reported. From March to April 2022, Niu and colleagues[12] began to try to apply 5G telesurgery to nephrectomy. First, three cases of nephrectomy were performed. The main surgeon operated the bedside operating system (slave system) of three primary hospitals in other areas (the network communication distance is 82.5 km, 141.0 km and 229.0 km, respectively) in the Affiliated Hospital of Qingdao University through the control console (main system) and used 5G wireless communication technology to transmit images and operation instructions to perform the remote nephrectomy. The results showed that all three cases of telesurgery were successfully completed. The network latency of the three cases was 27.3 ms on average, and no packet loss occurred. The total latency was 177.3 ms on average. The average operation time was 79.3 min. The average amount of intraoperative blood loss was 31.1 mL, and no network-related adverse events occurred during the operation. Reexamination 30 days after the operation showed no obvious abnormalities in the patients, and all the patients recovered successfully after 6 months of follow-up, which preliminarily natively verified the safety and feasibility of 5G telesurgery in renal surgery.

Subsequently, the team conducted a further study and performed a total of 29 nephrectomies using 5G telesurgery[12], all of which were successfully completed with low postoperative pain and no postoperative complications (Figures 1 and 2). In this study, the median total latency was 176 ms, the cumulative round-trip distance was greater than 14 700 km, and the farthest surgical distance was about 1775 km. The results showed that the total latency of less than 200 ms was conducive for telesurgery, which further verified the feasibility of 5G telesurgery in kidney surgery. They present that the study initially identified three key elements that affect the smooth operation of telesurgery, namely high-speed and stable data transmission technology, safe and reliable surgical robot system, and smooth and skilled operator operation. In this study, the same surgeon successfully performed telesurgery on three patients located in different primary hospitals on the same day through network exchange, which is of great significance to alleviate the problem of difficult access to medical care due to the uneven distribution of medical resources in China.

FIGURE 1 Master operation side of telesurgery. The chief surgeon controls the master operation terminal of the telesurgical robot and remotely performs surgical manipulation through the network transmission device.

FIGURE 2 Salve operation side of telesurgery. The assistant on the patient's side follows up the operation process through the transmitted laparoscopic video, communicates with the chief surgeon through wireless devices, and assists the chief surgeon in telesurgery.

Alessandro Larcher et al.[21] also saw great value in the study, which highlighted the unique opportunities that 5G telemedicine could offer, especially the expansion of medical services in tertiary centers to areas with poor medical conditions, which could be extremely beneficial in alleviating a series of problems arising from the unequal distribution of medical resources. In addition, 5G remote technology can also be used for knowledge dissemination and surgical skills training, which was a new development direction of 5G remote technology. Vineet Gauhar et al.[22] believed that the successful development of this study preliminarily validated the feasibility of large-scale promotion of 5G telesurgery.

In April 2022, Ji et al. at Peking Union Medical College Hospital and Li et al. at Peking University First Hospital collaborated to complete a pyeloplasty using 5G technology[23]. During the surgery, Ji operated a domestic surgical robot system to perform surgery on a patient located 6 km away, completing key surgical steps without serious intraoperative complications or technical failures. The console time and control swap time were 98 min and 3 s, respectively. The mean latency time was 271 (range, 206–307) ms. The operation was accurate, the surgery was completed successfully, and the patient recovered well after surgery. This telesurgery differred from previous telesurgeries by the innovative use of a dual console model. Applying this mode, the local surgical team can perform surgical operations under the careful observation and real-time supervision of the telesurgical team, reducing surgical risks.

4.3 | Application of 5G telesurgery in adrenal surgery

In 2022, Niu and colleagues[24] conducted the first clinical trial of 5G telesurgery applied to adrenal surgery. Fifteen patients came from three primary hospitals in other regions, which were 82.5, 199, and 250 km away from the hospital where the surgeon was located. The remote robotic surgical system used in the surgery was MicroHand S robotic surgical system. The operating table controlled by the surgeon (the main system) and the bedside operating system (the slave system) where the patient located were connected through the 5G network provided by China Mobile. The results showed that all 15 cases were successfully completed, with an average network latency of 32.5 ms, an average total latency of 182.5 ms, an average operation time of 48.6 min, and an average amount of blood loss of 28.76 mL. No postoperative complications occurred, and all the patients recovered smoothly. No significant complications or obvious abnormalities were found in the postoperative follow-up laboratory tests and computed tomography, which initially verified that the application of 5G telesurgery to adrenal surgery was completely feasible.

4.4 | Application of 5G telesurgery in prostate surgery

In March 2022, Liang et al.[25] from Anhui Medical University performed a laparoscopic radical prostatectomy using the 5 G + 4 K intelligent wireless lumpectomy with independent intellectual property rights, and the surgery was successfully completed. The intelligent lumpectomy system applied in the operation had the features of high-definition, miniaturization, wireless, and intelligence, which can carry out cloud storage, artificial intelligence analysis, mobile remote consultation, remote demonstration, and so on. Moreover, experts from higher level hospitals could implement remote guidance for the operation with the help of the 5G network, which further verified the feasibility of 5G telesurgery applied to prostate cancer surgery.

4.5 | Application of 5G telesurgery in andrology surgery

In 2022, Zhou et al.[26] reported a clinical trial of 5G telesurgery applied to andrology surgery, in which a surgeon applied a domestic surgical robot system in Nanjing to perform laparoscopic surgery for varicocele on two patients from Xinjiang, located 3800 km away, with an operation time of 40 and 45 min, respectively, with no more than 5 mL of blood loss and an average network latency of 130 ms, and no intraoperative network adverse events occurred, and both operations were completed successfully. The success of this experiment fully illustrated the promising application of 5G telesurgery in the field of andrology surgery.

4.6 | Application of 5G telesurgery in lithiasis surgery

In 2022, Zhou et al.[26] applied a remote ultrasound diagnostic system to perform a 5G remote ultrasound-guided percutaneous nephrolithotomy on a patient located 3300 km away in Xinjiang, with an operation duration of 50 min and a blood loss of 10 mL. No residual stones were found on the second day of postoperative review, with an intraoperative one-way data transmission delay of 70 ms and an occasional data packet loss rate of 5%. This experiment fully validated the feasibility of 5 G telesurgery applied to stone surgery.

5 | LIMITATIONS OF THE APPLICATION OF 5G TELESURGERY IN UROLOGY

Although existing studies can preliminarily verify the feasibility of 5G telesurgery in urology, the limitations of the application in the current situation have also been exposed during the research process. First of all, the stability of the surgical robotic system is particularly important in telesurgery. In recent years, domestic surgical robots have developed rapidly and there are more research results proving their reliability, but in some 5G remote surgery procedures, there are still occasional adverse events[24], although the duration is short and the solution is simple, it will reduce the fluency of surgery. To some extent, it interferes with the procedure. Moreover, 5G telesurgery has a high requirement for the total system latency. Although the latency of domestic robot systems participating in 5G telesurgery has been reduced to a relatively ideal level[12,24,27,28], there is still room for further reducing the latency and improving the speed. At present, telesurgery robots are still in the preliminary development stage in China, and their technical development and related problems faced need to be explored continuously.

In addition to the factors of the surgical robot, the surgeon's anatomical knowledge, surgical skills, proficiency in robot operation, and adaptability to latency are also crucial to compensate to a certain extent for disruptions caused by network latency or lack of robot coordination, thus increasing the safety of the surgery. How to conduct standardized training for surgeons and their surgical teams involved in telesurgery is also an important issue to be solved in the promotion process of 5G telesurgery.

Network security and information confidentiality are essential for the promotion of 5G telesurgery. Cyberattacks can cause severe modifications in haptic feedback, prolong surgery times, and even complete loss of control of the surgical robot, resulting in patient harm. Although no serious cyberattacks have occurred on remote robotic systems today, secured by end-to-end encryption and authentication technologies, additional security measures are needed to ensure surgical safety and information confidentiality.

Alessandro Larcher et al.[21] suggest that there is still considerable debate about the cost-effectiveness of 5G telesurgery. In Niu's study, for example, the two most distant hospitals are located in Gansu Province and Qingdao, 1700 km apart. Assuming that the average cost of a round-trip flight from Gansu Province to Qingdao is $231, the $70 000 cost of the transmission equipment could theoretically cover the travel expenses of 300 patients. Of course, whether a strategy to support patient travel to a tertiary care center is more cost-effective than telesurgery requires rigorous economic analysis and should take network and maintenance costs into account.

In addition, the above-mentioned series of studies on the application of 5G telesurgery in urology had a small number of cases, a single surgical procedure, a short follow-up period, and a single-arm study, so there are some limitations, and the follow-up needs to increase the sample size and carry out a variety of urologic telesurgery to draw more scientific and valid conclusions.

To sum up, as a groundbreaking new technology, 5G telesurgery is completely feasible in urology, but at present, there are a series of problems and limitations, which need to be solved by further research in the future.

6 | PROSPECT OF 5G TELESURGERY IN UROLOGY

At present, the application of 5G telesurgery in urology is still in the stage of exploration and research, but according to the current research results, its feasibility and safety are beyond doubt. In the future, 5G telesurgery can not only be applied to kidney surgery and bladder surgery but also be explored in more urological surgery, such as prostate surgery, lithiasis, andrology diseases, urinary system trauma, and so on. In the future, with the increasing amount of 5G telesurgery and the enrichment of remote surgery experience and data, the performance of surgical robots—especially domestic surgical robots—can be better targeted and improved for better application in 5G telesurgery, which is of great significance in alleviating the difficulty of access to medical care due to the uneven distribution of medical resources and in enabling people in areas with less developed medical resources to receive high-quality medical services in the future[29,30].

The application of 5G technology makes high-quality image and audio transmission possible. Under the support of 5G technology, 4K or even 8K ultra high-definition image transmission can be realized. At the same time, the image can be combined with the patient's three-dimensional (3D) model and virtual/augmented reality imaging to enable surgery in a remote 3D field of view and provide the surgeon with a high-definition vision from all angles. This will greatly improve the surgeon's sense of presence during the operation, which can effectively improve the quality and safety of the operation.

With the promotion of 5G telesurgery in the future, there are a number of problems at the national level, such as the need for supporting laws and regulations related to telesurgery to protect the rights and interests of both doctors and patients, pricing of 5G telesurgery in urology, and medical insurance. In addition, the difficulty for patients to accept the new treatment model due to the deep-rooted traditional consultation concept, which is also a problem that will be faced during the promotion of 5G telesurgery in urology in the future. However, we believe that as the 5G telesurgery system continues to mature, people's awareness and acceptance of 5G telesurgery increases, and the national system of telesurgery continues to improve, in the near future, 5G telesurgery can greatly improve the treatment satisfaction rate and benefit the majority of patients.

AUTHOR CONTRIBUTIONS

Fanshuo Meng and Guangdi Chu designed the whole study and drafted the manuscript. Zhao Zhang, Hang Yuan, and Chengjun Li analyzed the data. Haitao Niu revised the manuscript. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest except for Haitao Niu, who is an Editorial Board Member of *UroPrecision*. He was excluded from the peer-review process and all editorial decisions related to the acceptance and publication of this article. Peer review was handled independently by the other editors to minimize bias.

DATA AVAILABILITY STATEMENT

All data of this study would be available from the corresponding author upon reasonable request.

ETHICS STATEMENT

Not applicable.

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