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Telerobotic Spinal Surgery Based on 5G Network: The First 12 Cases

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Objective: The purpose of this study was to determine the efficacy and feasibility of 5th generation wireless systems (5G) telerobotic spinal surgery in our first 12 cases.
Methods: A total of 12 patients (5 males, 7 females; age, 23–71 years) with spinal disorders (4 thoracolumbar fractures, 6 lumbar spondylolisthesis, 2 lumbar stenosis) were treated with 5G telerobotic spinal surgery. Sixty-two pedicle screws were implanted.
Results: All patients had substantial relief from their symptoms. Screw placements were classified using Gertzbein-Robbins criteria. There were 59 grade A, 3 grade B. Mean operation time was 142.5 ± 46.7 minutes. Mean guiding wire insertion time was 41.3 ± 9.8 minutes. The deviation between the planned and actual positions was 0.76 ± 0.49 mm. No intraoperative adverse event was found.
Conclusion: 5G remote robot-assisted spinal surgery is accurate and reliable. We conclude that 5G telerobotic spinal surgery is both efficacious and feasible for the management of spinal diseases with safety.

Keywords: Telemedicine, Remote surgery, Telesurgery, Robotic surgery, Orthopaedics, 5G

INTRODUCTION

The robot technique has recently entered clinical use in the orthopedic area. It increases the accuracy and process repeatability of implant placement and has a great potential in making a better and safer clinical outcome for orthopedic operation.[1] With a booming of the technology revolution, operational techniques and implants in spinal surgery continue to develop through these years.[2] In spinal fusion surgery, the accuracy of pedicle screw fixation can be increased significantly with the application of computer-assisted robotic system.[3] After several years of development, testing, and research, the TiRobot system has been proved to be reliable and efficacious in full-length spinal surgery.[4-12]

Remote surgery is based on the mutual telecommunication of medical information. Medical information, such as image, audio, and video, are digitized and transmitted via cable or wireless telecommunication networks. Surgeons can manipulate the surgical robot to perform operations from a distance via the networks.[13,14] The system delay and instability of the network have been the main obstacles of the real-time remote surgery. However, the recent revolution of the 5th generation wireless system (5G) makes real the practice of remote surgery. The 5G network has a spectacular performance in high speed, low latency, and high bandwidth.[15]

The breakthrough in surgical robot technology and the 5G network system makes real the practice of telerobotic spinal surgery. It also pushes further the development of "one-to-many" remote clinical patterns. In this study, we present 12 cases that underwent 5G telerobotic spinal surgery to determine the efficacy and feasibility.

MATERIALS AND METHODS

1. Equipment and Personnel Arrangement of 5G Telerobotic Spinal Surgery

(1) The 5G network: telecommunication network and equipment were provided and established by China Telecom (Beijing, China) and Huawei Technologies Co., Ltd. (Shenzhen, China).

(2) Equipment and personnel arrangement in hospitals with patients underwent operations (the patient side): surgical robot system (TiRobot system), C-arm, carbon fiber operating table, high-definition cameras and monitors, surgeons, and robot engineers. Local surgeons placed K-wire and screws, supervised the movement of the robot, and performed decompression if necessary. Robot engineers set up the navigation and took 3-dimensional images for registration or verification.

(3) Equipment and personnel arrangement in the master control room located in Beijing Jishuitan Hospital: multiple monitors, high-definition cameras, robot workstation, audio equipment, the leading surgeon, and network engineers. The leading surgeon performed screw planning and robot manipulation.

2. Hospitals Information

There were 6 hospitals from 6 different cities in China involved in these clinical case series: Beijing Jishuitan Hospital (the telesurgery center where the master control room located), Shandong Yantaishan Hospital, Zhejiang Jiaxing Second Hospital, Tianjin First Central Hospital, Hebei Zhangjiakou Second Hospital, and Xinjiang Karamay Central Hospital.

3. Patients Data

After approval by the Bioethics Committee (ID: 20181106), and obtaining informed consent from the patient, 5G telerobotic spinal surgeries for 12 patients were accomplished until now. The average age of 12 patients was 52.5 (range, 23–71 years). Four of 12 patients were diagnosed with a thoracolumbar fracture, 6 were with lumbar spondylolisthesis, 2 were with lumbar spinal stenosis. Sixty-two pedicle screws were implanted. All patients have been notified about 5G telerobotic surgery and signed informed consent forms before the operation. Patients' demographic data were shown in Table 1.

4. Operation

The operation was performed according to the guideline for thoracolumbar pedicle screw placement assisted by orthopaedic surgical robot.[5] After anesthesia, the patient was prone on the Jackson table. The patient tracker was placed at the spinous process of 1 to 2 vertebrae cranial to the operative segments. The registration plate was assembled to the robot arm and be placed to the appropriate position in the operative field. Three-dimensional images were harvested using motorized C-arm. Images were transmitted to the master control room in Beijing Jishuitan Hospital remote surgery center via the 5G network system. Pedicle screw placement planning was accomplished on the specific software in robot workstation. The robot surgeon chose entry point and 3-dimensional convergence orientation of the screw. Under the guidance of navigation with remote control, the guiding tube of the robot arm was moved to the target place. Then, the K-wire and screw were placed along the robot guiding tube by surgeons on the patient side. Surgeons on the patient side performed the rest of the procedures of the operation (Figs. 1, 2).

5. One-to-Many Cases

For example, the master control room (Beijing Jishuitan Hospital), hospital A (Shandong Yantaishan Hospital), and hospital B (Zhejiang Jiaxing Second Hospital) were involved in the one-to-many operation. After 3-dimensional images were acquired from the operating room A. Radiographic data were transmitted to the master control room. The surgeon in the master control room remotely manipulated the robotic arm to the position

Table 1. Patients' demographic data (n = 12)

Variable	Value
Age (yr), mean (range)	52.5 (23–71)
Sex	
Male	5
Female	7
Operation level	
T11	1
T12	3
L1	4
L2	3
L3	3
L4	5
L5	7
S1	5

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of each pedicle screw he planned. When the robotic arm reached the planned position, the surgeon in the operating room A was notified to insert the K-wire. After all K-wires were implanted, the position of the K-wires was confirmed by 3-dimensional images or 2-dimensional fluoroscopy. The surgeon in the operating room A started to insert the pedicle screws, and the surgeon in the master control room started surgery on patient B. The surgeon in the master control room also performs the screw planning and robot manipulation of the operating room B, and the local surgeon completed the placement of K-wires and screws. When the surgeon in the operating room B started to insert the pedicle screws, the surgeon in the master control room was informed to confirm the screws of the patient A. If the screw position was correct, the surgeon in the operating room A continued to complete the remaining steps. The surgeon in the master control room then confirmed the screws of the patient B. After verification, the surgeon in the operating room B continued to complete the remaining steps (Fig. 3).

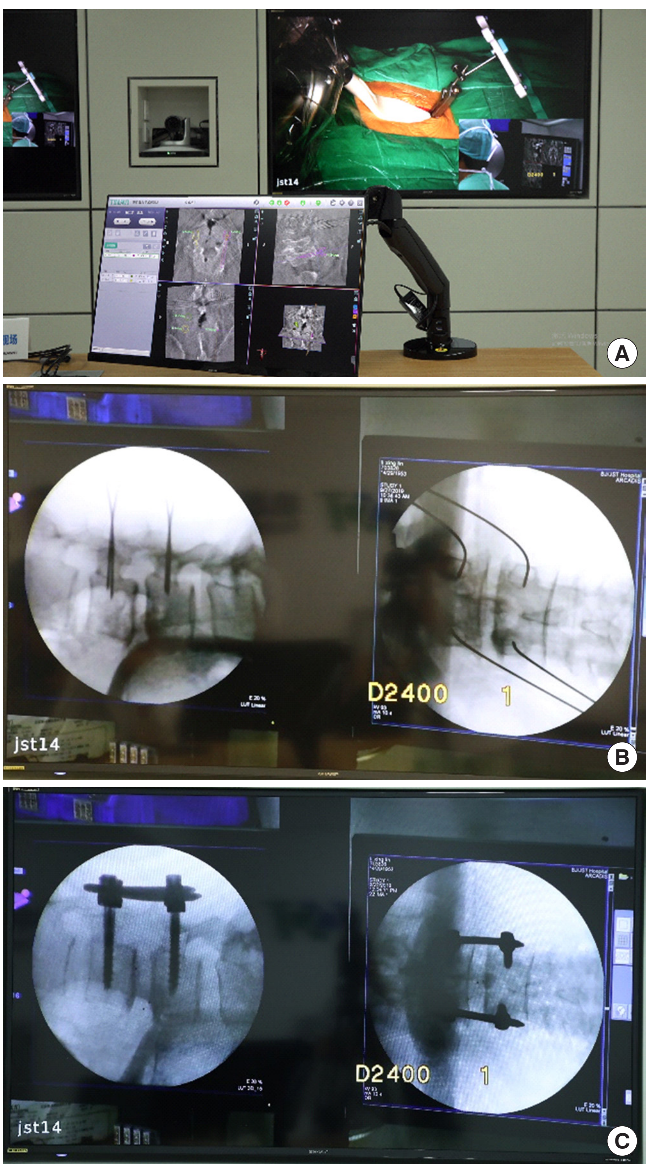

Fig. 1. (A) Screw planning at master control room. (B) K-wire placement. (C) Screw placement.

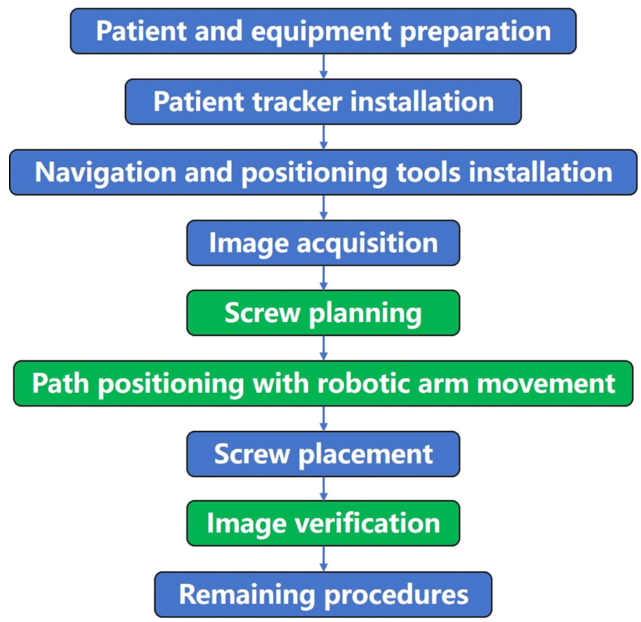

Fig. 2. The workflow of 5G (5th generation wireless systems) telerobotic spinal surgery. The blue background indicates the steps performed by surgeons on the patient side, and the green background shows the steps performed by the leading surgeon in the master control room.

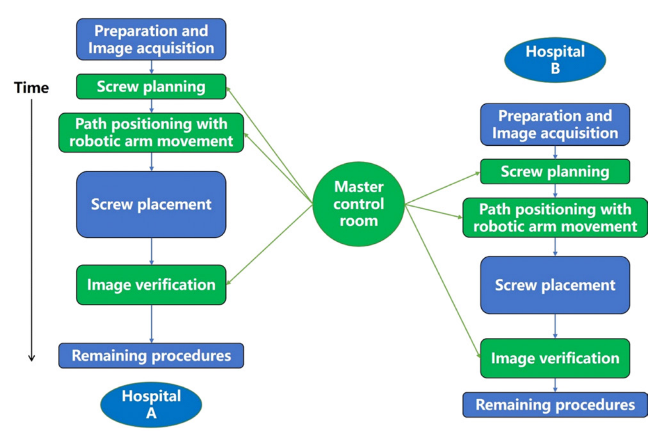

Fig. 3. The workflow of “one-to-many” 5G (5th generation wireless systems) remote orthopedic robot-assisted surgery.

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6. Evaluation

1) Accuracy of pedicle screw placement

Accuracy was evaluated using Gertzbein-Robbins criteria.[16] According to pedicle cortical breaches by the screw, each screw was and classified into 5 grades: grade A, no cortical breach; grade B, breaches < 2 mm; grade C, breaches < 4 mm; grade D, breaches < 6 mm; grade E, breaches ≥ 6 mm. The deviation between the actual position of the screw and the planned position was equal to the mean value of deviation between the entry point and end point in the fusion image.[12] Measurement was accomplished by 2 independent blinded surgeons on the postoperative computed tomographic images. In case of disagreement on grading, adjudication was made by group discussion. The mean value of the deviation results of 2 surgeons was calculated as the deviation result.

2) Intraoperative adverse event and 5-day postoperative complication

Adverse events and complications were recorded. The intraoperative adverse event included but not limited to telecommunication failure, robot system error, neurovascular injury. Postoperative complications included but not limited to delayed vascular injury, nerve root injury, spinal cord injury, cerebrospinal fluid (CSF) leak, infection.

3) Operation time

Operation time was recorded from the beginning of incision to the end of wound closure. The guide-wire insertion time was recorded from the beginning of patient tracker placement to the end of K-wire placement.

RESULTS

The operations of 12 patients were performed using the 5G telerobotic surgery system. All operations were performed as planned. The mean network latency of all these operations was 28 ms, reported by China Telecom. No network adverse event was observed. Mean operation time was 142.5 ± 46.7 minutes. Mean guiding wire insertion time was 41.3 ± 9.8 minutes. Sixty-two pedicle screws were implanted. Fifty-nine screws (95.2%) were grade A in Gertzbein-Robbins criteria, and 3 screws were grade B. The acceptable rate (grades A and B) of pedicle screws was 100%. The deviation between the planned and actual positions was 0.76 ± 0.49 mm. No intraoperative adverse event was found. One patient whose preoperative diagnose was lumbar spondylolisthesis was found CSF leak the next day after the operation. It was considered not related to the robotic manipulation of the screw implant but related to the nerve decompression procedure.

A total of 2 "one-to-many" 5G remote orthopedic robot-assisted surgery were successfully performed. In June 2019, we conducted the one-to-two simultaneous surgery in Beijing, Shandong, and Zhejiang. In August 2019, the one-to-three simultaneous surgery was completed in Beijing, Xinjiang, Hebei, and Tianjin. In 2 "one-to-many" cases, plural patients underwent surgery at the same time. The surgeon in the master control room alternately completed the core steps of multiple robot-assisted remote operations. All operations were performed as planned. No network adverse event was observed.

DISCUSSION

Robot-assisted spinal surgery has been a popular and reliable surgical technique for recent years.[1,7,12,17-24] Roser et al.[24] reported that the accuracy of pedicle screw placement in SpineAssist robot-assisted spinal surgery was 99%. Lonjon et al.[25] claimed that the accuracy of pedicle screw placement using the ROSA robot system was 97.3%, compared with 92% using freehand method. According to the previous study, by using the TiRobot system, 95.3% of pedicle screws were classified as grade A in Gertzbein-Robbins criteria, compared with 86.1% using freehand method.[12] According to meta-analysis of Li et al.,[26] the accuracy of robot-assisted pedicle screw placement was significantly higher than the freehand method.

Previous researches on robot-assisted orthopedic surgery focused on the local control robot system. There was no report about telerobotic spinal surgery based on the 5G network and "one-to-many" surgery. In this study, all pedicle screw presented with accurate placement, and the deviation between planned and actual position was less than 0.8 mm. No intraoperative adverse event was found. The result recommended that telerobotic spinal surgery based on the 5G network was safe and reliable.

Remote surgery can build a connection between surgeons and patients located in isolated areas. It shows great potential to perform a complicated operation for rural area's patients who are lack of medical resources. Telerobotic spinal surgery through the 5G network could significantly improve the quality and safety of the surgery. Due to the uneven quality of surgery across the country, this technical progress allows patients in remote areas to receive remote surgery operated by the top experts without traveling thousands of kilometers. It also makes multicenter co-operation possible.[27]

Since the first remote surgery in 2001,[13] the development of remote surgery has been slow and full of difficulties. One of the major obstacles is the limit of the network system. 5G network is the newest generation of the telecommunication system. It is possible to provide minimal latency, high bandwidth, and reliable communication for medical service.[28,29]

There was no telecommunication error nor network delay that might interfere with operation procedures in these 12 cases. When communication failure occurs, surgeons on the patient side can also complete the robot-assisted spinal surgery without a remote control. However, a severe adverse event could happen as a result of communication failure. The key factor influencing remote surgery is the speed of the telecommunication network. The high speed of the 5G network could conquer the obstacle of transmission latency and instability. The previous study suggested that a 200-ms system delay could lead to a fatal consequence when a complicated and challenging remote surgery was performed.[30] There was no malfunction for the robot system in these 12 cases. The previous studies demonstrated that the malfunction and registration failure rate of the spinal robot system was 1%, and 85.7% adverse events were related to the misoperation of surgeons.[31,32] In this way, except for keep promoting the robot system, the practice of operation skill and manipulation of the robot system are also critical to the success of robot-assisted surgery.[33]

These clinical case series also explored the new pattern of "one-to-many" remote surgery. In "one-to-many" remote surgery, one surgical expertise can provide surgical care for patients who are physically isolated at once. It makes better use of the resources of surgical expertise to provide high-quality medical services for more patients. In previous, the "one-to-many" remote clinical pattern was significantly restricted by the limit of network bandwidth. Remote surgery is particularly sensitive to the network delay, and its safety could be substantially affected by latency. However, with the assist of the 5G network, the bandwidth is not a limit anymore. There is only very low latency when several remote surgeries performed with fluency at the same time. One "one-to-three" telerobotic surgery was performed in these clinical case series, and it is believed that a higher amount of simultaneous multicenter remote surgery is possible, according to the vast potential of the 5G network. Moreover, dislike the real-time endoscopic robotic system such as DaVinci robot, navigation-assisted spinal robot (such as TiRobot system) allows enough time for man-machine interacting, thus guarantees more safety and reliability in remote surgery.

These cases were our initial experience with the collaboration of the 5G network and the orthopedic robot system. It shows great potential in future telemedical service, especially for patients in rural areas or extreme environments (such as underwater, battlefield, or in space). For now, the best indication of telerobotic spinal surgery is for senior surgeons guiding complicated screw placing from a distance. Meanwhile, the current indication of telerobotic spine surgery is still limited by the robot technique of spine surgery. Except for pedicle screw placement, the previous article also reported the application of robot technology in the guidance procedure of percutaneous transforaminal endoscopy and vertebroplasty surgery, anterior odontoid screw fixation, posterior C1–2 transarticular screw fixation, cortical trajectory for pedicle fixation, and translaminar lag screw fixation.[2-12] More complicated telerobotic cases would be performed based on the 5G network in the future. Not only spinal surgery could benefit from this high-speed network, but also other surgeries like cardiac surgery, urinary surgery, and hepatobiliary surgery. The combination of the DaVinci Surgical System and the 5G network may be promising in remote surgery.

Although the current robotic system has already shown a great convenience in screw positioning of complicated and deformed structures, a reliable new robotic system for bone grinding and nerve decompression is required for further development of spinal telesurgery. Telesurgery requires the collaboration of surgeons from both sides in these 12 cases. Surgeons on the patient side performed the procedures besides screw positioning. To ensure the safety and effectiveness of the telerobotic spinal surgery, the training for surgeons on the patient side to collaborate with robot engineer was also very important.

CONCLUSION

Telerobotic spinal surgery based on the 5G network is accurate, safe, and reliable. The application of the 5G network in the clinical area has great potential and value in the future.

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SUPPLEMENTARY MATERIAL

Supplementary video clip 1 can be found via https://doi.org/10.14245/ns.1938454.227.

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