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WebRTC and 5G Based Remote Control System for a Vascular Intervention Robot

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***Abstract*- Cardiovascular and cerebrovascular diseases are significant health issues that threaten human life. They typically develop insidiously and progress gradually, but when an event occurs, the consequences can be severe. These conditions often manifest suddenly and acutely, necessitating prompt treatment due to a very short therapeutic window. Vascular interventional surgery is the preferred treatment because of its rapid efficacy and brief recovery time. However, the procedure demands a high level of expertise and exposes physicians to radiation, and there is an uneven distribution of skilled doctors across different regions. The advent of vascular interventional surgical robots not only protects physicians from radiation exposure and improves procedural accuracy and safety but also enables remote interventions. Based on a robotic platform for vascular interventions, our team has developed a remote vascular interventional system that leverages WebRTC and 5G networks. This system ensured that the transmission latency for control commands and imaging meets clinical requirements, and our remote clinical experiments have demonstrated its feasibility and safety.**

***Index Terms*- Remote Surgery, Interventional Robot, 5G Network, Control System, WebRTC.**

I. Introduction

Cardiovascular and cerebrovascular diseases refer to conditions affecting the heart or blood vessels, including coronary artery disease, cerebrovascular disease, arrhythmias, and heart failure. These diseases are the number one killer of human health. According to the Global Burden of Disease study, over the past 30 years, the number of people with cardiovascular diseases has increased from approximately 270 million to 520 million, and the number of deaths has risen from 12.1 million to 18.6 million. World Health Organization statistics indicate that cardiovascular and cerebrovascular diseases are the leading cause of death worldwide, claiming nearly 17.9 million lives each year, with most deaths occurring in low- and middle-income countries. Although vascular interventional surgical robots perform well, providing radiation protection and assisting surgeons in precise operations, they lack a highly responsive and reliable remote teleoperation solution. They are unable to enable vascular interventional procedures over long distances [1].

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In grassroots hospitals, which suffer from inadequate equipment and a shortage of skilled physicians. When a patient experiences a stroke, in tandem with this loss, brain tissue—and the functions it controls, such as movement, speech, cognition, and emotion—gradually deteriorates. If immediate rescue efforts are not undertaken, the patient may eventually become disabled or even die. Each year, more than two million people die due to delayed stroke treatment or missed emergency intervention windows. According to data from the Chinese Stroke Big Data Observation Platform (BOSC), only 11.79% of acute ischemic stroke patients seek medical attention within three hours of symptom onset, while nearly 50% do not arrive until after 24 hours, by which time the efficacy of available treatments is severely limited. This delay likely leads to disability or death in almost half of the patients. Moreover, urban areas—with their superior transportation and richer medical resources—show nearly twice the rate of timely treatment compared to rural regions or areas with less developed healthcare systems. The advent of 5G communication technology offers robust support to improve the balance in healthcare resource distribution and to safeguard the critical “golden window” for stroke rescue [2].

French company Robocath has introduced the R-One robotic system, which consists of a radiation-shielded control console and an interventional surgical robot. It uses a joystick to control the slave-side robot's delivery of catheters and guidewires, and its open architecture ensures compatibility with mainstream interventional devices. German company Siemens has developed the CorPath GRX system, which integrates a slave control unit with a master console. Featuring both linear and rotational degrees of freedom, it can select the appropriate interventional devices based on the doctor’s requirements and the patient's condition, while also offering intelligent assistance features. American company Microbot Medical has launched the Liberty robot—a compact, single-use, remotely operated interventional surgical robot that is compatible with most commercial guidewires and catheters. Its disposable design helps reduce maintenance costs and hospital capital expenditures. Additionally, a team at MIT has developed a magnetically controlled flexible robot that navigates inside blood vessels via a robotic arm and magnetic control platform; once it reaches the target location, the doctor can insert or retract the catheter to establish a vascular treatment pathway. [3]-[5].

The above studies employ a separated architecture between the operational controller and the assistive robot, using remote operations to reduce doctors' exposure to radiation.

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However, their functionality remains incomplete, and they have yet to achieve fully remote interventional procedures.

Building upon the team's previous research in vascular interventional surgery robots, we have conducted an in-depth exploration to address the issue of unequal distribution of medical resources [6]-[18]. We have designed a remote interventional surgery robot control system based on 5G networks and the WebRTC (Web Real-Time Communication) framework, which supports real-time remote medical image transmission and low-latency control commands. The contributions of this paper are as follows:

a) We proposed and designed an end-to-end remote vascular interventional surgery robot control system with encryption protection. The system achieves an operation control command delay of less than 55ms and an image transmission delay of less than 260ms, meeting the requirements of clinical surgeries.
b) The effectiveness, safety, and stability of the solution were validated through in-vivo clinical trials.

This Section clarifies the background significance and problems that need further improvement. The second section will introduce the overall framework.

II. Overview of Pan-vascular Intervention Robot

The research platform consists of three main components in Fig.1. The first component is the vascular interventional surgical robot operator, which adopts a dual push-pull lever natural interaction design. The left lever controls the catheter, while the right lever controls the guidewire or rapid exchange instruments. Buttons and toggle switches allow clinicians to set instrument linkage or switch control modes based on clinical needs. This dual-lever operation mimics traditional manual techniques, enabling doctors to adapt to the vascular interventional surgical robot more efficiently using their clinical experience. The second component is the interventional robot actuator, which consists of three delivery modules: the pre-positioned delivery module is responsible for axial delivery and retraction of the catheter; the intermediate delivery module controls radial rotation of the catheter, intermediate catheter delivery, and rapid exchange instrument delivery; and the rear positioned delivery module manages radial rotation of the intermediate catheter and rotational delivery of the guidewire. The third component is the remote interventional surgical system, which categorizes data into command and multimedia types. Command data follows a TCP-UDP hybrid strategy, where TCP handles business logic and UDP ensures command transmission, while multimedia data is based on the WebRTC framework. The vascular interventional robot control commands do not pass through a server but are instead directly connected to the remote controller via a P2P network. Meanwhile, multimedia devices in the operating room, such as DSA, panoramic cameras, and microphones, are connected to a remote server, which is responsible for data acquisition.

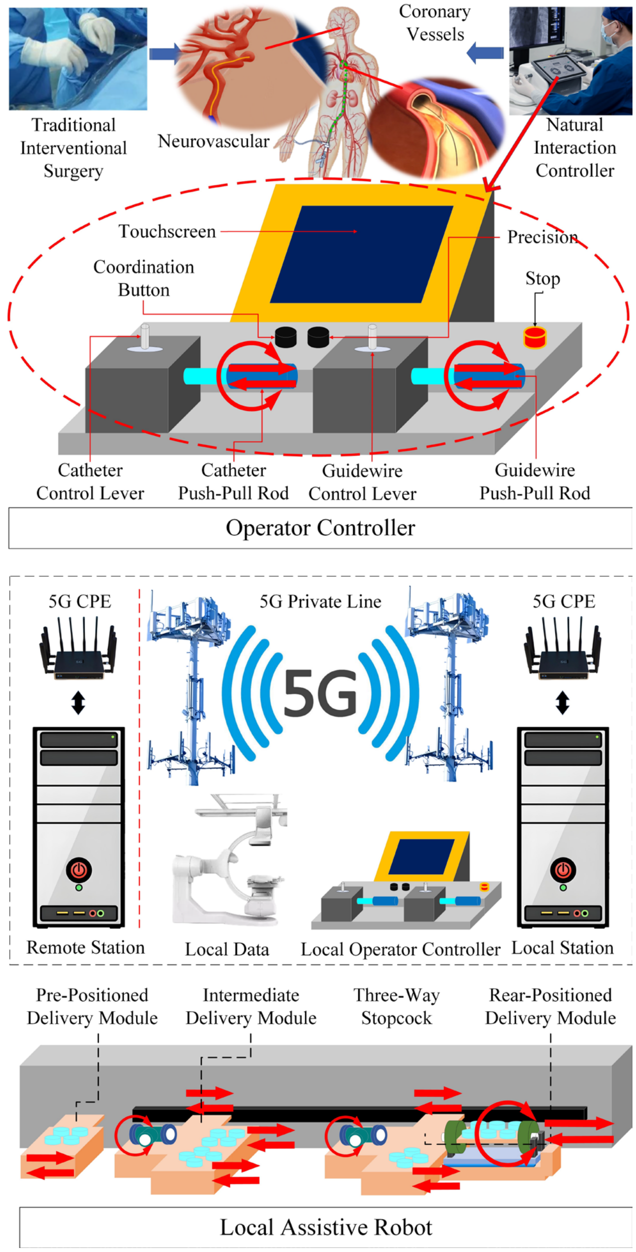

Fig. 1. Function diagram of vascular intervention robot.

III. Design of Remote Control System

A. Communication Architecture Design

Fig. 2 illustrates the network architecture of the vascular interventional surgical robot remote surgery system. At the bottom layer, the device layer integrates network ports, video data, and audio data, which are then processed through the WebRTC framework core to establish a P2P transmission network, ensuring low-latency and high-quality data exchange. Data compression, transmission, and rendering are completed via corresponding encoders and decoders, optimizing real-time performance. The vascular interventional robot controller is directly connected to the 5G network, utilizing end-to-end encryption to ensure secure.

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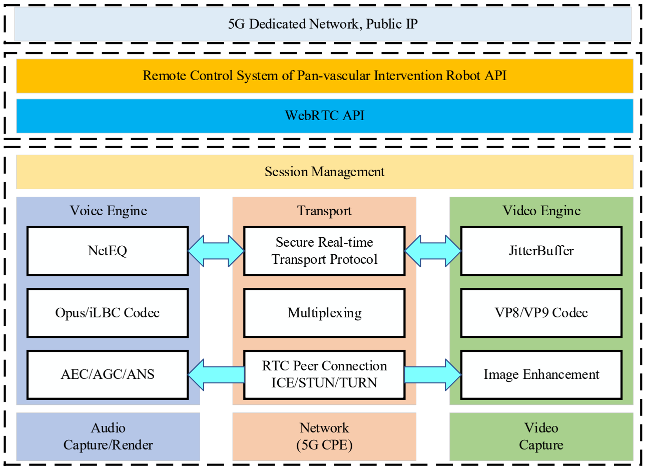

Fig. 2. Remote Communication Architecture.

B. *Safety Control Strategy Design*

TABLE I
SURGICAL SAFETY CONTROL STRATEGY

Initialization	$Q_{\text{net}} = f(P_{\text{loss}}, L_{\text{latency}}, J_{\text{jitter}})$ $C_{\text{control}} \in \{C_{\text{remote}}, C_{\text{local}}\}$ $C_{\text{control}} = C_{\text{remote}}$	(1)
While True Do	$Q_{\text{avg}} = \frac{1}{N}\sum_{i=1}^{N} Q_{\text{net}}(t_i)$	(2)
If	$Q_{\text{avg}} < Q_{\text{threshold}}$, $C_{\text{control}} = C_{\text{local}}$	(3)

The system utilizes a dedicated access channel on a commercial 5G network, established through a custom Access Point Name (APN) service provided by the telecom operator. Although the system employs public IP addressing for interoperability and remote accessibility, the underlying data path is logically isolated and prioritized within the operator's infrastructure, ensuring reliable and high-performance communication. As shown in Table 1, during the system initialization phase, network quality is calculated using Equation 1, and the remote doctor gains control. During the surgical procedure, network quality is continuously evaluated using Equation 2, which applies a moving average filter to assess network stability. By setting an adaptive window size, the system reduces the impact of network jitters, preventing unintended control switching. If network quality falls below the threshold, the system will switch to local mode, ensuring surgical safety and stability by using Equation 4.

$$Q_{\text{net}} = \omega_1 e^{-k_1 P_{\text{loss}}} + \omega_2 \frac{1}{1+e^{k_2(L_{\text{latency}} - L_{\text{opt}})}} + \omega_3 \max\left(1 - \frac{J_{\text{jitter}}}{J_{\max}}, 0\right) \quad (4)$$
$$\omega_1 + \omega_2 + \omega_3 = 1$$

The packet loss rate has a significant impact on network quality and is evaluated using an exponential decay function, where k_1 serves as the adjustment factor. Network latency is assessed based on its deviation from the L_{opt} using a Sigmoid function, with k_2 controlling its influence. Jitter, which affects the perception of real-time control, is measured using a linear decay function, where J_{max} represents the maximum acceptable jitter. The overall network quality is evaluated using weight coefficients, allowing the system to adjust the weighting ratios according to different surgical requirements. This approach ensures optimized network performance.

In tele surgical systems, the quality of network communication plays a vital role in ensuring operational safety and control stability. Experimental studies have shown that packet loss, jitter, and latency affect system performance in different ways. Among them, packet loss is the most critical, as even a rate of 2%–3% may cause command loss, control delays, or desynchronization between the surgeon's console and the robotic system. These issues can directly reduce surgical precision and compromise feedback reliability. Therefore, maintaining a highly reliable connection with near-zero packet loss is essential.

Jitter, defined as the variation in packet arrival times, affects the predictability of system behavior. When jitter exceeds 10–20 ms., it can lead to unstable visual or haptic feedback and make precise control difficult.

On the other hand, moderate and stable latency can be tolerated. For example, command delays under 80 ms. and audiovisual delays under 300 ms. are generally acceptable if they remain consistent and are managed through system design and operator adaptation. Recent preclinical studies in China have confirmed that remote surgery can be performed safely with total latencies ranging from 170 to 320 ms.

The design of a reliable tele surgical network should follow a clear priority: minimize packet loss first, reduce jitter second, and manage latency within a stable range [19].

TABLE II
PARAMETER CONFIGURATION

Parameter	Value	Description
ω_1	0.60	Weight of packet loss
ω_2	0.15	Weight of latency
ω_3	0.25	Weight of jitter
k_1	15.0	Packet loss sensitivity
k_2	0.03	Latency sigmoid slope
L_{opt}	80ms.	Target latency for control
J_{max}	20ms.	Maximum acceptable jitter

In the evaluation of tele surgical network performance, a baseline environment was established with default parameters: control command latency of 50 ms., jitter of 10 ms., and packet loss rate of 1%. Based on this configuration, each key factor packet loss, latency, and jitter were independently varied within clinically relevant ranges: packet loss from 0% to 10%, latency from 20 ms. to 400 ms., and jitter from 0 ms. to 100 ms. The network quality score Q_{net} was computed for each condition. When the score approached the critical $Q_{\text{threshold}}$ of 0.65, the corresponding parameter values were approximately: 2.42% packet loss, 173.5 ms. latency, and 18.18 ms. jitter. These values can serve as practical threshold criteria for triggering system warnings or initiating control handovers in tele surgical applications. The parameter settings are summarized in Table II and Fig.3.

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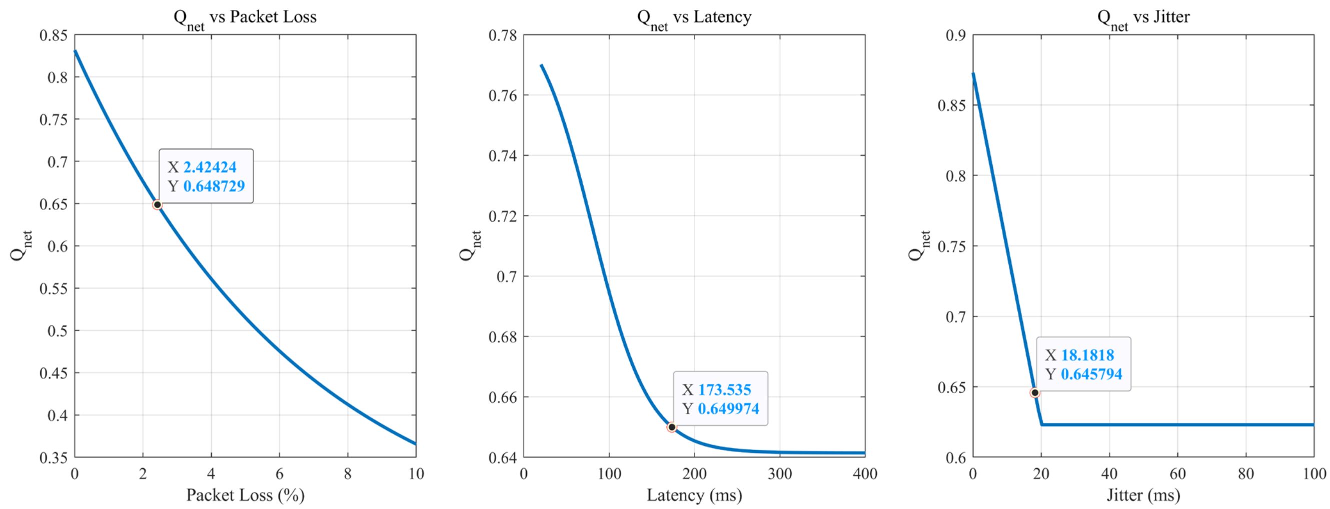

Fig. 3. Network Quality Score Q_{net} Under Varying Latency, Packet Loss, and Jitter Conditions

IV. Experiments

A. Kinematics Performance Measurement

This section consists of two parts. The first part involves testing a remote vascular interventional surgical robot system. As shown in Fig.4, the experimental setup, a control room was established at Shanghai Zhongshan Hospital, while another control room and the interventional surgical robot were set up at Kashgar Second People's Hospital in Xinjiang. The dual-control room setup allows for seamless switching of the primary operator's control when needed, providing an additional layer of safety. By analyzing latency data during testing, the reliability of the remote-control system was validated. The second part presents a remote human clinical interventional procedure conducted over nearly 5,200 km. Through the collection of key indicators and evaluation of the clinical procedure, the safety and efficacy of the remote-control system were successfully demonstrated.

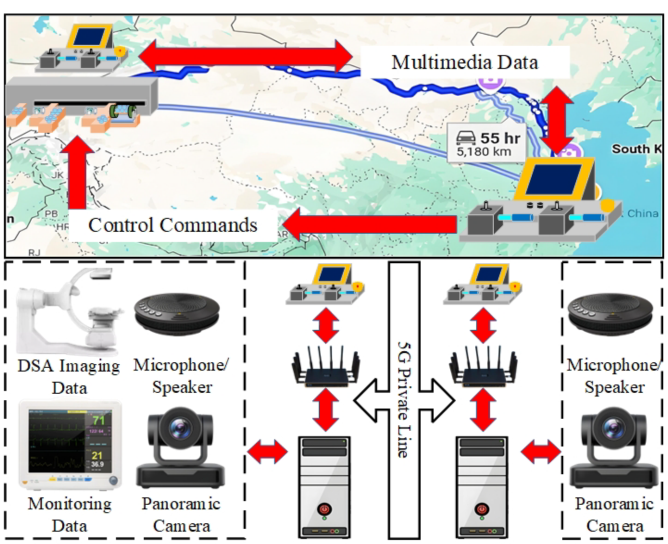

Fig. 4. Experimental Setup.

TABLE III

THE DELAY IN COMMAND TRANSMISSION

Direction	Mean	Max	Min	SD
SH to XJ	53.48ms	59ms	50.5ms	2.4ms

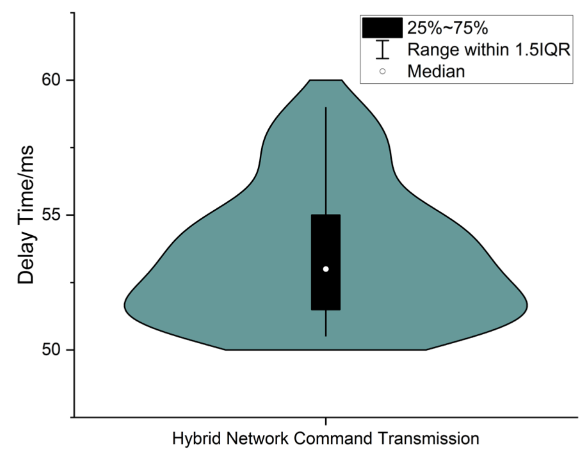

Fig. 5. Delay of Commands Transmission

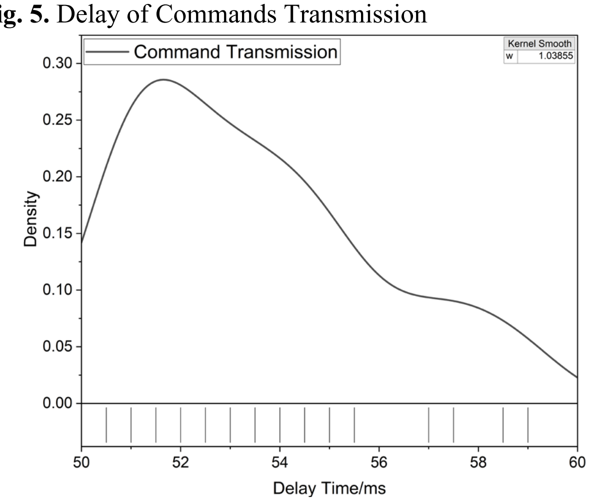

Fig. 6. Delay Distribution of Command Transmission.

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TABLE IV

THE DELAY IN MULTIMEDIA TRANSMISSION

Direction	Mean	Max	Min	SD
XJ to SH	261ms	310ms	220ms	20.6ms
SH to XJ	257ms	300ms	224ms	20.6ms

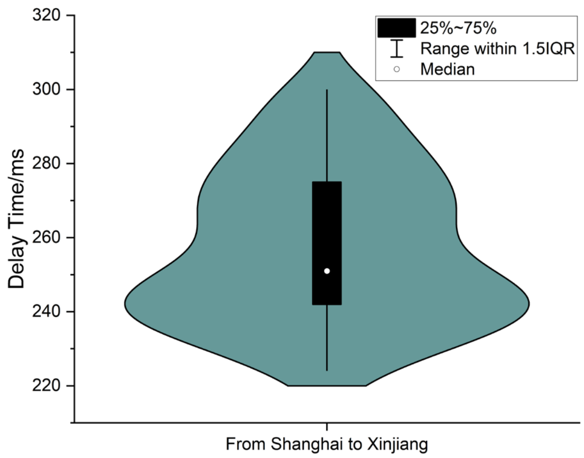

Fig. 7. Delay from Shanghai to Xinjiang.

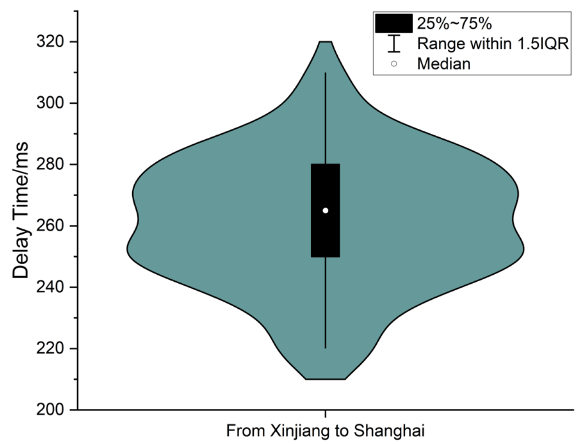

Fig. 8. Delay from Xinjiang to Shanghai.

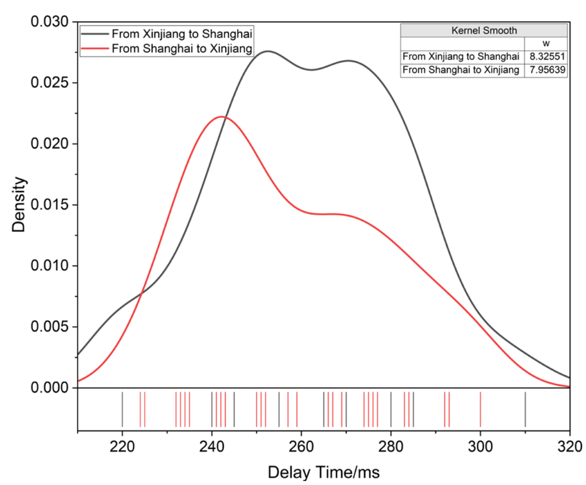

Fig. 9. Delay Distribution of Multimedia Transmission.

The command transmission data in Table III was collected at different time periods on the same day. The average latency was 53.48 ms. In Fig. 5 and 6, the overall interquartile range (IQR) data contains no outliers, indicating a relatively stable distribution of command transmission latency. The highest probability density is concentrated near the peak latency range (50–52 ms.). The latency of multimedia data, as shown in Table IV, indicates an average delay of 261 ms. from Xinjiang to Shanghai and 257 ms. from Shanghai to Xinjiang, with minimal difference between the two directions. As illustrated in Fig. 7 and 8, the IQR data contains no outliers, confirming the stability of the transmission.

B. Remote Scientific Clinical Surgery.

TABLE V

EFFECTIVENESS EVALUATION

Evaluation	Feasibility	
Primary Efficacy Evaluation Indicators	**Clinical Success:** Completion of left and right coronary angiography, implantation of a stent in the left anterior descending artery, and balloon dilation of the subtotal occlusion in the circumflex branch.	
	Technical Success: The procedure was successfully and smoothly performed with vascular intervention robot under remote control system by the doctor.	
Secondary Efficacy Evaluation Indicators	Total Procedure	106 min
	Angio Completion	6 min
	Guidewire Crossing	LAD: 7 min
		LCX: 11 min
	Fluoroscopy	35 min 06 sec
	Radiation (Subject)	176.70 μSv
	Radiation(Operator)	0.36 μSv
	Contrast Usage	300 ml
Safety Indicators	No perioperative **MACE** (Major Adverse Cardiac Events), **AE** (Adverse Event), or **SAE** (Serious Adverse Event) occurred, with a device defect incidence of 0%.	

We conducted a clinical trial to evaluate the safety, efficacy, and stability of a remote vascular intervention robotic system at Zhongshan Hospital in Shanghai and Kashgar Second Hospital in Xinjiang. The details are shown in Table V.

The subject, a 53-year-old patient, was admitted one month ago with acute myocardial infarction. The right coronary artery showed 20-30% stenosis in the proximal segment, with a 100% occlusion in the mid-segment, resulting in a TIMI (Thrombolysis in Myocardial Infarction) flow grade of 0. Percutaneous coronary intervention (PCI) was performed. The left main coronary artery showed no significant stenosis, while the mid-segment of the left anterior descending artery exhibited diffuse disease with 70-80% stenosis, and TIMI flow grade 3 was observed. The patient underwent elective PCI. Subsequently, the patient returned to Kashgar Second Hospital due to recurrent chest pain. After thoroughly reviewing the patient's medical records and obtaining prior

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approval from the hospital's ethics committee, we decided to proceed with the remote vascular intervention using the robotic system for the surgery.

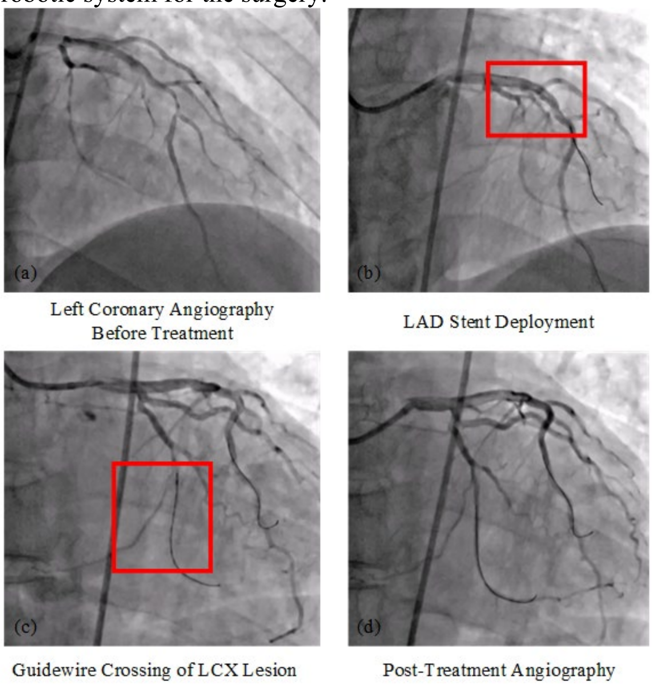

Fig. 10. Clinical Procedure Angiographic Images.

The procedure began with coronary angiography, revealing an 85% severe stenosis in the mid-left anterior descending artery (LAD) and a near-total occlusion in the mid-left circumflex artery (LCX), with the vessels appearing narrow and tortuous. The doctor remotely navigated the guiding catheter to the left coronary ostium and precisely manipulated both the main branch guidewire and the side branch protection guidewire to cross the stenotic lesion, establishing a passage before accurately deploying the stent, as illustrated in Fig.10(b). Subsequently, the doctor advanced the interventional device through the subtotal occlusion in the LCX and performed a simple balloon angioplasty in Fig.10(c).

CONCLUSION

This paper proposed a remote vascular interventional system based on a vascular interventional surgical robot platform, integrating WebRTC and 5G networks, and proposed a safety assurance strategy. Since vascular interventional surgery primarily involves the control of flexible instruments, which rely on passive force support to navigate through blood vessels, latency is a more critical factor than precision. Therefore, performance testing was conducted, revealing an average command transmission latency of 53.48 ms. and an average multimedia data transmission latency of 259 ms. Finally, by analyzing the clinical key indicators from a remote human interventional procedure spanning nearly 5,200 km, the system's safety and efficacy were successfully validated.

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