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From Lab to Clinic

Expanding Surgical Frontiers Across the Pacific Ocean: Insights from the First Telesurgery Procedures Connecting Orlando with Shanghai in Animal Models

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Abstract

Background and objective: Telesurgery is as a promising solution to support and deliver advanced health care services to underserved areas. The primary endpoint of our study was to prove the concept of low-latency long-distance connectivity and to describe the feasibility of remote surgery.
Methods: A prospective study was conducted from February 29 to March 1, 2024, in live animal models (porcine) connecting surgeons from Orlando (USA) to the animal laboratory in Shanghai (China) using 5G and Wi-Fi connections, in combination with continental and transpacific fiber. We performed ten radical nephrectomies and two partial nephrectomies in five animals using the MicroPort MedBot robotic platform. Intraoperative and telesurgery connection variables were reported with a descriptive statistical analysis.
Key findings and limitations: No complications or conversions were reported. The mean animal weight was 38.2 (35–40) kg, the mean operative time was 32.7 (21–45) min, and the mean blood loss was 23.3 (20–30) ml. The mean latency was 296 (±50) ms. Findings from animal studies may not always translate directly to human outcomes.
Conclusions and clinical implications: We described the feasibility of transpacific low-latency telesurgery in live porcine models with no intraoperative complications. Achieving optimal low-latency connectivity via telecommunication networks was essential for effectively performing the surgical procedures. However, we still need further investigation to achieve even lower latencies for human trials. We found that long-distance telesurgery is safe and feasible in animal models. However, it is a complex practice, and we still need further studies before translating these results to human trials.

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Patient summary: Our research has demonstrated the feasibility of low-latency long-distance telesurgery in live animal models. However, this type of telesurgery is a complex procedure, and further work is needed to translate these results to human trials.

1. Introduction

Global health care inequity due to restricted access to quality surgical care is a colossal humanitarian issue. In many parts of the planet, the majority of the populations have limited or no access to any surgical treatment options [1]. The World Health Organization has stated that annually over 300 million surgeries are performed worldwide, but an additional 143 million are required to address global needs properly [1]. These regions, which lack basic or advanced surgical care, lead to an amplification of social inequality and delay in societal evolution.

In underserved areas, access to appropriate surgical interventions is critical to addressing health care disparities, promoting social equity, and improving quality of life [1]. Telesurgery is emerging as a promising solution, offering the potential to bridge the health care access gap by facilitating remote surgical training, education, and support, and delivering advanced health care services [2,3]. By reducing health care disparities, there is the potential to reduce patient mortality and permanent sequelae from delayed or inappropriate treatments in all areas of surgery, with the most urgent needs being cardiovascular, neurological, and oncological surgery [4].

The Lindbergh operation performed in 2001, between New York (USA) and Strasbourg (France), described the feasibility of telesurgery across the Atlantic Ocean [5]. However, the adoption of remote surgery in the following two decades was restricted by technological, economic, and philosophical limitations. Recent advances in more diverse and potentially more economical robotic systems and progress in telecommunication technologies, notably the advent of high-speed Internet connections, 5G networks, and advancements in fiber optics, have revolutionized the landscape of telesurgery, paving the way for its integration into mainstream health care [6–8].

The telecommunication challenge for telesurgery is quite vast as inherent surgical latency increases with distance and variability in the transmission network. The longer the distance, the less efficient the transmission and the longer the surgical latency of the audio and video image. Increased latency would affect the surgeon's ability to synchronize his/her movements with that of the distant robot and patient, potentially leading to inability to coordinate the two.

Given these challenges, the efficacy and performance of robotic technologies and network connections for long-distance telesurgery (exceeding 10 000 km) are yet to be fully understood. Thus, we conducted a pioneering prospective study on telesurgery in live porcine models by establishing a telerobotic connection between Orlando (USA) and Shanghai (China) via the Pacific Ocean. This connection covered a round-trip distance of approximately 26 000 km. Our goal was to study the feasibility of teleremote control as a function of distance and teleconnectivity. The concept of our study was to prove the hypothesis of low-latency long-distance connectivity and to describe the feasibility of remote surgery in distances longer than 10 000 km.

2. Materials and methods

On February 29 and March 1, 2024, we performed a prospective study in live animal models (porcine) connecting two surgeons (V.P. and M.C.M.) from Orlando (USA) with the animal laboratory in Shanghai (China) using 5G and hospital fiber (accessed via corporate Wi-Fi), in combination with continental and transpacific fiber. The 5G connection was initially attempted, but the Wi-Fi had better speed and performance, so we selected the hospital fiber (Wi-Fi) to perform the whole trial. In this study, we used five animals to perform ten radical nephrectomies and two partial nephrectomies with the MicroPort MedBot (Shanghai MicroPort MedBot Group Co., Ltd., China) robotic platform. One assistant from the animal laboratory in Shanghai assisted in placing the clips and changing the instruments.

The primary endpoint of our study was to prove the concept of low-latency long-distance connectivity and describe the feasibility of remote surgery in animal models in distances longer than 10 000 km. Safety was defined as the possibility of performing the specified procedure without a risk to the animal's life and without the need for conversion to other surgical modalities (open or laparoscopic). Feasibility was defined as the possibility of performing the predetermined surgeries (partial and radical nephrectomies) with acceptable network delays, which were defined as delays that would not prevent us from performing all the necessary surgical steps (dissection, resection, warm ischemia, and hemostasis). The secondary endpoints include calculating the details of data transmission, delays, and robot performance with perioperative data reports. Robot performance regards troubleshooting (recovered or unrecovered faults) or instrumentation problems during the procedure.

2.1. *Animal selection*

Before the study, the research project was submitted to the Experimental Animal Ethics Committee from Timely Horse (Shanghai) Laboratory Animal Equipment Co., Ltd, Shanghai (China). All steps of this research project followed the appropriate institutional animal care and regulatory body requirements from the country where the animals were located (China). Five animals (one male and four females) were used to perform ten radical nephrectomies and two partial nephrectomies. The partial nephrectomies were accomplished on both kidneys of the last animal. During the procedure, the communication between the surgeon (in the USA) and the assistant (in Shanghai) was performed in English.

2.2. Robotic platform with telesurgery capabilities

We used the multiport robotic platform named Toumai, produced by MicroPort MedBot (Shanghai MicroPort MedBot Group Co., Ltd.). This platform is composed of an immersive console (closed) and four robotic arms attached to a single patient-side kart (Fig. 1 and Supple-

Fig. 1 – Toumai robotic console in Orlando and the connection setup with the animal laboratory in Shanghai.

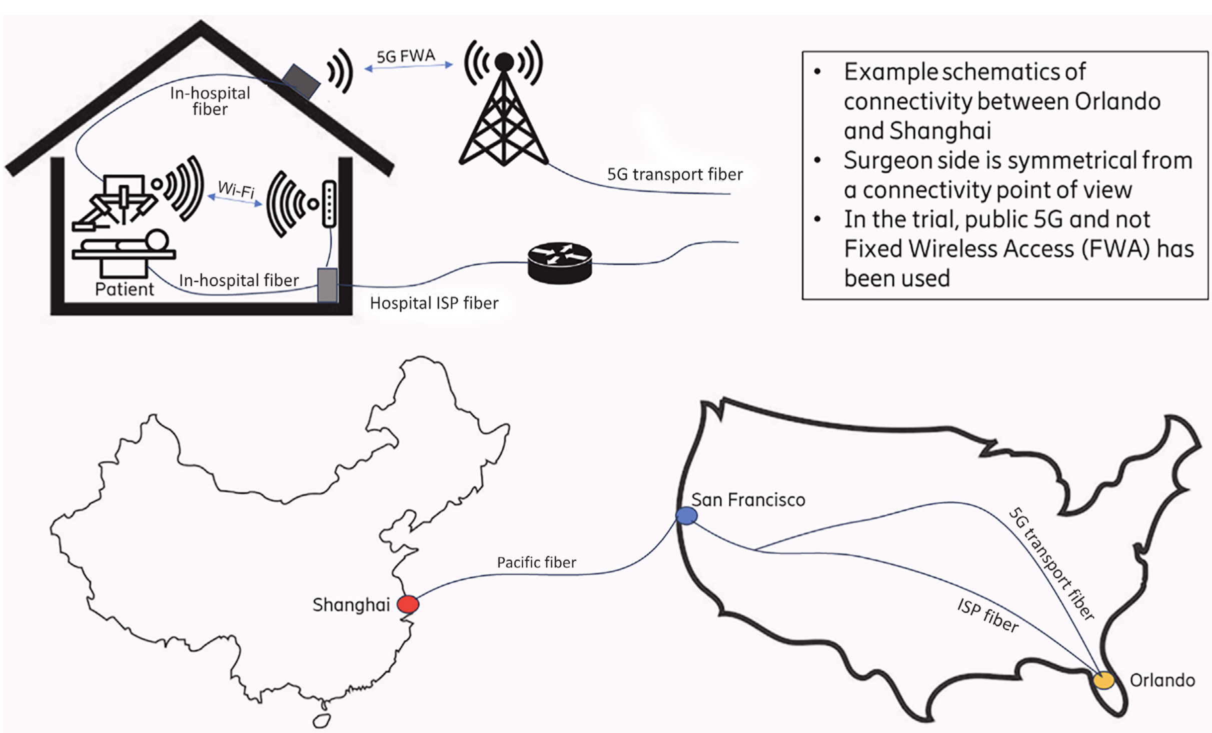

Fig. 2 – Schematic connectivity between Orlando and Shanghai with 5G and fiber illustration. FWA = fixed wireless access; ISP = Internet service provider.

mentary Fig. 1). This platform has three trocars for the instruments (8-mm diameter), while the scope trocar is of 11 mm and fits a 10-mm scope. Two types of scopes are available (0° and 30°), while several 8-mm instruments are also available (usually with ten lives each). In our study, we used the Cadiere bipolar scissors. Once using the 30° scope, it is possible to rotate the angle (30° up or down) using the touchpad on the console.

The console was located in Celebration, FL, USA, at our training facility (Nicholson Center), and the patient-side kart was in Shanghai (China) at Timely Horse (Shanghai) Laboratory Animal Equipment Co., LTD. The one-way geographical distance between both centers is approximately 13 000 km (Figs. 2 and 3). In this trial, we have used two different access methods: (1) hospital fiber accessed via a corporate Wi-Fi network and (2) a nonoptimized public 5G system. For both systems, we put a relay server in San Francisco to force the data from Orlando to pass through the optimum transpacific fiber cable.

2.3. *Surgical technique*

The animals were placed in a flank position. After general anesthesia and CO_2 insufflation, five trocars were placed; these included four 8-mm robotic trocars and an additional 12-mm trocar for the assistant. The most important criterion while performing multiport robotic surgery in any circumstance is to place the trocars at an appropriate distance of 8–10-cm between each other. We used scissors on the right side, as well as bipolar fenestrated and Prograsp on the left. In some cases, when the assistant had a difficult angle to apply the clips, we used the robotic Hem-o-lok clip applier (Fig. 4). For suturing, two needle drivers were used. Soon after the radical nephrectomy on one side, the position of the animal was changed to a flank position on the other side, and the other kidney was removed with the same technique.

2.3.1. *Radical nephrectomy*

Radical nephrectomy includes complete ligation of the renal artery, vein, and ureter with Hem-o-lok clips or sutures. We started the procedure by dissecting through the layers of

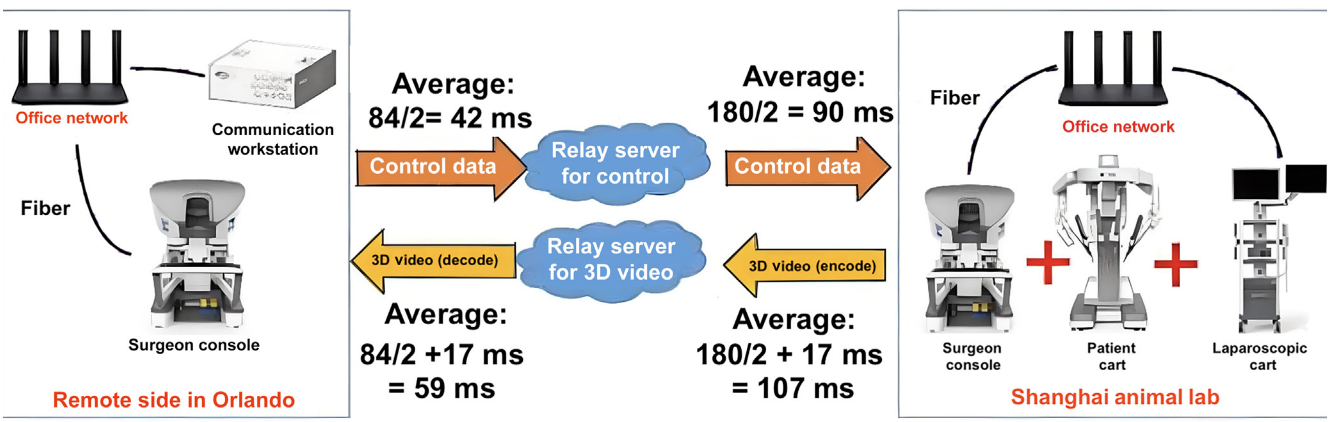

Fig. 3 – Total latency = control latency (Orlando to server) + control latency (Shanghai to server) + 3D video (encode to server latency) + 3D video (to server latency + decode) = 42 + 89 + (42 + 17) + (89 + 17) = 296 ms. 3D = three dimensional.

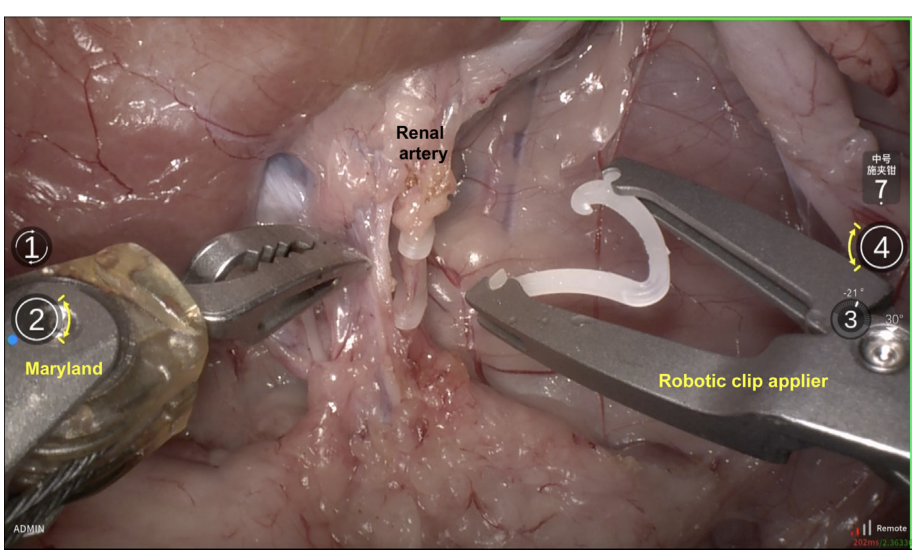

Fig. 4 – Illustration of the robotic clip applier.

perirenal tissue to expose the kidney and surrounding structures. In sequence, the kidney was mobilized until the renal hilum (artery and veins) and ureter were identified. After dissecting each structure individually, we used Hem-o-lok clips to ligate the artery, vein, and ureter. In some animals with more than one artery or vein, we used the robotic clip appliers due to their ability to achieve better clip angulations than the assistant. In one case, we performed vein and artery ligation with a 2-0 Vicryl suture.

2.3.2. Partial nephrectomy

Partial nephrectomy was defined as renal parenchyma removal with subsequent defect closure with Vicryl suture anchored with Hem-o-lok clips. On the last animal, before performing radical nephrectomy, we isolated the renal artery and vein, and placed bulldog clips for warm ischemia. In sequence, a 3 × 3 cm^2 defect on the anterior part of the kidney was performed (Fig. 5) to simulate a tumor enucleation defect. The lesion was closed with a 2-0 Vicryl suture and Hem-o-lok clips at each edge of the defect (Fig. 6). In sequence, the bulldog clips were removed, and hemostasis was checked. Finally, we clipped the renal artery, vein, and ureter with Hem-o-lok clips and completed the last two radical nephrectomies of the study.

3. Results

3.1. *Cohort demography and perioperative outcomes*

Table 1 illustrates the characteristic of each animal and type of surgery performed. The first four animals underwent radical nephrectomies, and the last animal underwent bilateral partial nephrectomies with warm ischemia, followed by

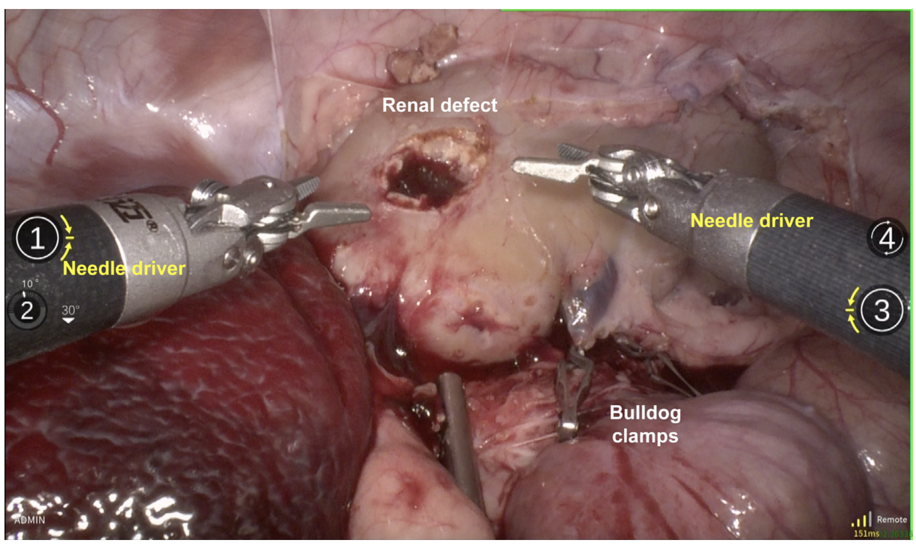

Fig. 5 – Partial nephrectomy defect during warm ischemia with bulldog clamps on the renal hilum.

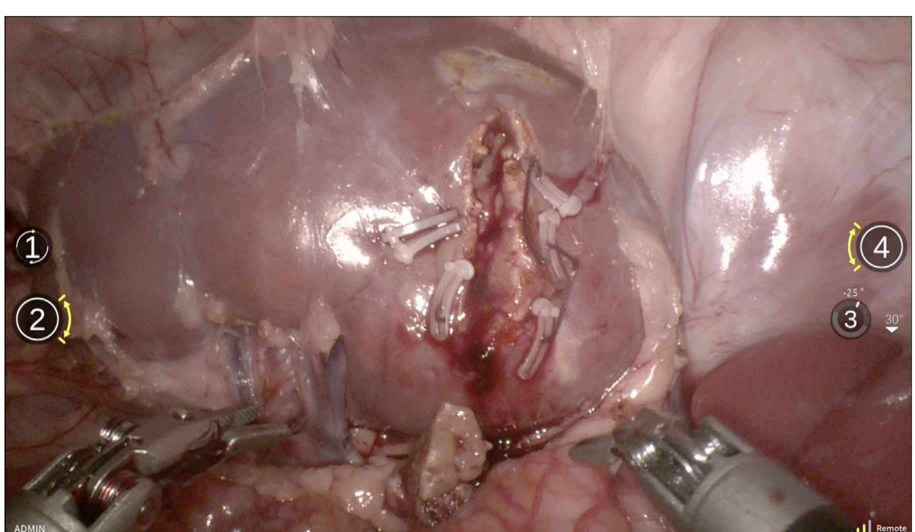

Fig. 6 – Renal defect closed with Vicryl and Hem-o-lok clips.

Table 1 – Description of the five animals used in the study (cases 1–5) and the side of the surgery

Case	Animal weight (kg)	Procedure	Operative time (min)	Complications	Number of arteries	Number of veins	Blood loss (ml)	Warm ischemia (min)
1 Left side	35	RN	45	None	2	2	20	NA
1 Right side	–	RN	23	None	1	1	–	NA
2 Left side	37	RN	21	None	1	1	0	NA
2 Right side	–	RN	33	None	2	1	0	NA
3 Left side	40	RN	32	None	3	3	0	NA
3 Right side	–	RN	36	None	1	2	0	NA
4 Left side	39	RN	35	None	2	1	30	NA
4 Right side	–	RN	31	None	1	1	–	NA
5 Left side	40	PN + RN	36	None	1	1	20	18
5 Right side	–	PN + RN	35	None	1	2	–	21

NA = not applicable; PN = partial nephrectomy; RN = radical nephrectomy.
The last column describes the warm ischemia time during the last two procedures.

bilateral radical nephrectomies and complete ligation of renal artery, vein, and ureter. No intraoperative complications or conversions were reported. The machine had optimal performance because we did not have any issues related to the robotic technology, such as instruments, and recovered or unrecovered faults. Only intraoperative complications were assessed because after the trial, the animals were sacrificed. The median animal weight was 39 (37–40) kg, and the median operative time was 34 (31–36) min. Blood loss was 20 ml for the first animal and 50 ml for the last animal due to two partial nephrectomies.

3.2. *Network configuration results*

Figure 3 describes the details of the mean latency delays calculated by the computer during the broadcast, including control latency (Orlando to server), control latency (Shanghai to server), three-dimensional (3D) video (encode to server latency), and 3D video (to server latency + decode). Adding 42 + 89 + (42 + 17) + (89 + 17), we found 296 (±50) ms of mean latency (Fig. 3).

For the first networking configuration, Wi-Fi added <10 ms round-trip latency. The end-to-end round-trip latency yielded a mean of 250 ms. The system did not experience major congestion during the operations, thus exhibiting a fairly low jitter.

For the second networking configuration, the mean of the round-trip latency was in the order of 375 ms, that is, approximately 100 ms slower than the hospital fiber solution. The additional 50 ms per direction are attributed to a longer fiber path through the operator transport network and poor 5G reception in the operating theatre having caused retransmissions and thus additional delays.

4. Discussion

Since the groundbreaking Lindbergh operation in 2001, where Marescaux et al [5] performed a transatlantic cholecystectomy using the Zeus robotic system and transatlantic telecom fibers, telesurgery has been relatively dormant. Initially considered a major advancement in surgical technology, the early years saw limited progress due to technological limitations and high costs associated with remote surgical interventions. However, recent advancements in robotic surgery technology, telecommunication infrastructure, and surgical techniques have revitalized interest in telesurgery, making it a more viable option for enhancing global health care access.

Recently, our surgical team was allowed to travel to China, and with approvals, we were able to remotely perform telesurgery for robotic radical prostatectomy over distances between 1500 and 2700 km between the surgeon and the patient using Toumai MicroPort MedBot and other robotic machines [9,10]. Each performed well, and the procedures were not affected by any perceptible surgical latency, with average surgical latency over the Chinese telecom of under 100 ms. This surgical experience demonstrated the feasibility of telesurgery over medium-range surgical distances within China. The efficacy over longer distances is still unknown, as the challenge of speed of transition in relation to distance and the switching between telecom networks adds an added dimension of instability. The surgical latency over long distances and multiple telecom networks is an open and unknown area of study.

Telesurgery holds immense humanitarian promise for revolutionizing surgical practice by transcending geographical barriers and providing access to expert surgical training, education, and patient care in remote and underserved areas. Telesurgery, if performed correctly, offers the potential of global health care equity. Modern robotic systems, high-speed Internet connectivity with 5G, modern fibers, and advanced imaging capabilities have enabled skilled surgeons to perform complex procedures remotely with precision and efficiency. However, challenges persist, particularly concerning network connections over long distances. Delays or disruptions in communication known as latency can affect the real-time control of robotic instruments, potentially compromising surgical outcomes. Ensuring seamless and reliable remote surgical interventions, especially across vast distances, and overcoming these technical limitations remain a priority in advancing the field of telesurgery. Our study was designed to evaluate the possibility of low-latency connectivity and remote function over extreme distances of a robotic system between the USA and China connected via a diverse telecom network and transpacific cable.

The Lindberg operation reached 6200 km across the Atlantic Ocean using a transatlantic cable with direct connection and more predictable latency of 155 ms. Our intention was to study a transpacific connection with a longer distance, and required the use of local Wi-Fi telecom at both the proximal and the distal end and a transpacific cable in between. The diverse international connectivity and the long surgical distance increased surgical latency significantly. However; by adjusting our network connectivity, our server, and our router, we were able to adjust the latency to 250 ms with minimal jitter. This latency was not optimal as <150 ms is preferred, but it was sufficient to complete our tasks safely and effectively. We performed successful procedures in live animal models with a round-trip distance of 26 000 km across the Pacific Ocean. Prior to the trial, our team completed 2 d of training in dry and animal laboratories in Shanghai, China. Given our extensive experience with the multiport platform, we did not notice much difference when working with the MicroPort robot. We believe that the learning curve is minimal, and surgeons experienced with multiport platforms should have no difficulty adapting to this new robot.

Even though this transpacific connection brings optimism, there are still several challenges before translating these results into human clinical applications. A robust network connection is essential to achieve appropriate connectivity for performing the surgeries between Orlando and Shanghai adequately, and a series of tests were conducted in the weeks preceding our trial. We learned that each robot has different processing power and a variable ability to connect at distance. We also had to navigate and optimize the signal by modifying the telecom network and the routing of the signal. The connectivity was not a plug and play scenario, with advanced engineering and telecom teams required to work with the surgical team. Our collaborative community was able to navigate these challenges and reduce surgical latency from 480 to 250 ms after a significant amount of thought. This reduction improves the surgeons' skills significantly because it is known that delays of <100 ms are optimal in terms of instant perception during surgery [11].

The established networking connection facilitated real-time communication between the surgeon and the robotic system, ensuring precise control and timely feedback during the surgical procedure. The network requirements for telesurgery typically involve high-speed, low-latency, and reliable connectivity to minimize delays and ensure smooth operation. Telesurgery requires high-speed data transmission to transfer video, audio, and control signals between the surgical site and the remote site where the surgeon is located. High-speed Internet or dedicated networks capable of transmitting a large amount of data are necessary to maintain the continuity of the surgical procedure without interruptions. We could connect with different networks, but after testing 5G and hospital fiber networks, we opted to use the latter due to the more stable signal: median 250 ms with hospital fiber (accessed via corporate Wi-Fi) versus 375 ms with public 5G.

Low latency is also crucial to ensure that the surgeon's commands are executed by the robotic system without perceptible delay. Minimal latency helps maintain the surgeon's control and coordination during delicate surgical maneuvers, reducing the risk of errors or complications. This is especially important during steps where the surgeon manipulates vessels, such as the dissection of the renal hilum. In addition, recent studies described the potential benefits of virtual reality and artificial intelligence integration into robotic surgery with the Metaverse concept, which could also benefit surgeons and patients while optimizing outcomes [12,13]. In our experience, the Wi-Fi network also provided fewer delays than 5G (median 250 vs 375 ms).

The networking segment between Orlando and Shanghai relies heavily on continental and transpacific fiber, which introduces significant latency due to the speed of light being approximately 30% slower in fiber than in free space. The shortest possible round-trip latency for the 26 000 km distance is theoretically 130 ms, but real-world factors increase this latency. Routing paths between endpoints, often determined by Internet service providers and telecom operators, play a crucial role, with some routes adding more delays than others. Additionally, network congestion in large metropolitan areas such as San Francisco and Shanghai further exacerbates these delays, particularly during peak hours. Wireless connections, such as Wi-Fi and 5G, also contribute to latency, making Wi-Fi more susceptible to congestion.

Furthermore, the total latency experienced by the surgeon in telesurgery systems is not just limited to networking delays. It also includes data processing latency, which can result from video compression or delays in robotic equipment, and the surgeon's reaction time. End-to-end security is another critical consideration, with 5G offering a more comprehensive system security than Wi-Fi. As telesurgery continues to evolve, managing these various sources of latency and ensuring robust security will be essential for delivering effective remote surgical procedures.

Operating in real time through network connections introduces unique challenges, particularly concerning latency or delays in communication between the surgeon's commands and the robotic system's response. Initially, we found it challenging to synchronize our movements with the latency found in the network connection. A delay between the surgeon's input and the robotic system's execution can disrupt the usual flow of surgical maneuvers, requiring surgeons to anticipate and compensate for these delays. Over time, as we gained experience and familiarity with the telesurgery system, we developed strategies to mitigate the impact of latency on surgical performance while optimizing and adjusting the speed of our movements. In this context, initially, we chose to perform radical nephrectomies on the first four animals to familiarize ourselves with the delayed environment, focusing on operations with no blood loss. After gaining confidence, we moved on to partial nephrectomies, which are inherently more complex and pose greater risks to the animals than radical nephrectomies. Consequently, only the final animal underwent a partial nephrectomy.

After conducting our study, we are optimistic that some procedures performed via telesurgery between centers over long distances are feasible and safe for animal models. However, we still have several challenges and limitations before translating these results into human clinical trials, especially between different countries with diverse telecom networks and policies. Some questions still remain regarding the costs of telesurgery procedures. In synthesis, if we are trying to connect two centers with access to WI-FI or 5G, the primary investment required relates to the robotic platform and its associated maintenance costs. However, if one or both centers do not have access to this connection, the initial investment is much higher because it will depend on the fiber and telecom antenna infrastructure.

Despite its pioneering and innovative nature, our project is not devoid of limitations. First, findings from animal studies may not always directly translate to human outcomes due to species-specific differences in anatomy, physiology, and treatment responses. Second, due to the small sample size, the statistical power and generalizability of the findings may be limited. Third, the outcomes may be influenced by the expertise and experience of the surgical team (V.P. and M.C.M.), leading to variability in results between studies and institutions. Finally, the study design with a limited follow-up prevents the assessment of long-term outcomes and potential complications associated with the surgical procedures. Aside from these four factors, we are optimistic about our results and believe that we have a proof of concept that telesurgery between long distances is a reality. The technology that is currently available has expanded the idea of telesurgery beyond a scientific concept to a potentially lifesaving surgical modality.

In this context, before translating these results to humans and performing telesurgery among different countries, optimizing the connection to achieve optimal delays and stability compatible with the distance between centers is crucial by using a dedicated fiber and connection. Therefore, this delay would be around 130–150 ms (26 000 km round trip divided by the speed of light inside the fiber) with a stable connection. Furthermore, we still need international guidelines to ethically offer and perform long-distance surgeries in humans between two countries [9]. In the current landscape of telesurgery, the responsibility for managing complications or connectivity issues during remote surgery typically falls on the medical care provider, which includes the local hospital and surgical team. One of our goals is to collaborate with our international community of telesurgery experts to develop guidelines that can be adopted by any country considering the implementation of telesurgery. However, this task is challenging due to the varying local laws across different countries and even within the states of the same country, such as the USA. As we have highlighted in several of our group's publications [2,9,14,15] telesurgery is still in its early stages globally, and it is crucial to approach its adoption with caution to ensure that the highest standards of surgical outcomes and ethics are maintained.

5. Conclusions

Our study demonstrated, for the first time, the feasibility of transpacific low-latency telesurgery in preclinical settings, showing that it is possible and safe, with no major complications reported in animal models. Navigating the telecommunications network to achieve optimal low-latency connectivity was vital in performing telerobotic surgery. The surgical outcomes were comparable with standard surgeries. However, while we are optimistic about the potential humanitarian benefits of remote site telesurgery, we are also cognizant of the complex nature of the task and the potential challenges. Further improvements in latency networks and international collaborations are essential to take this forward to human trials.

Author contributions: Marcio Covas Moschovas had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Study concept and design: Moschovas, V. Patel.
Acquisition of data: E. Patel, Saikali, Gamal, Rogers, Oliva.
Analysis and interpretation of data: Moschovas, Dohler.
Drafting of the manuscript: Moschovas, V. Patel.
Critical revision of the manuscript for important intellectual content: Marescaux, V. Patel, Satava.
Statistical analysis: None.
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Supervision: V. Patel, Marescaux.
Other: None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.euros.2024.09.009.

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