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Technological Innovation and Clinical Application Prospects of Vascular Interventional Surgical Robots

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Abstract: As a cutting-edge technology in the field of medical robotics, vascular interventional surgical robots have made remarkable progress in recent years. This paper focuses on the technological innovations of vascular interventional surgical robots, with particular attention to the system developed by Xu's team that rapidly secured national patents through China's Green Innovation Fast-Track. The article elaborates on its key breakthroughs in haptic force feedback, master-slave control accuracy, and multimodal image fusion, and discusses the potential clinical advantages these innovations confer. By benchmarking the system against comparable technologies at home and abroad, the paper forecasts its future applications in healthcare and provides a reference for subsequent R&D and clinical adoption.

Keywords: Vascular interventional surgical robot; Technological innovation; Clinical application; Force-feedback mechanism; Master-slave control; Multimodal image fusion.

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1. Introduction

Vascular interventional surgery is a minimally invasive technique in which catheters, guidewires and other instruments are introduced percutaneously into the blood vessel to diagnose and treat lesions. It is widely used for coronary artery disease, cerebral aneurysms, peripheral arterial stenosis and other conditions. According to the China Cardiovascular Health and Diseases Report 2023, more than three million new cardiovascular cases arise each year in China, and the volume of endovascular interventions is growing at an annual rate of 15% [1]. However, conventional endovascular procedures rely entirely on manual manipulation, giving rise to three fundamental drawbacks. For instance:

(1) Physicians are exposed to high radiation doses (0.5–1 mSv per procedure);

(2) Device-placement accuracy is heavily experience-dependent; in complex lesions the success rate barely reaches 75–80 %;

(3) Prolonged static positioning induces operator fatigue that progressively degrades manual stability.

The convergence of robotics, advanced sensing, and medical imaging has spawned dedicated endovascular robotic systems. In 2003 the U.S. Food and Drug Administration (FDA) cleared the first such device, CorPath GRX, for coronary interventions, ushering the field into clinical practice [2]. China entered this arena later, yet has moved swiftly. The vascular-intervention robot developed by Xu's team is poised to break the long-standing international monopoly and establish a Chinese technological benchmark for cardiovascular therapy.

This paper examines the system from the perspectives of technological innovation, clinical application, and experimental validation, aiming to provide a reference for future advances in the field.

2. Background and current state of endovascular robotic systems

2.1. Limitations of conventional manual endovascular surgery

During the procedure the operating physician and assisting staff must remain under continuous fluoroscopic guidance, accumulating doses that markedly raise lifetime cancer risk, which is a pressing occupational-health hazard that has yet to be adequately resolved [3]. Moreover, procedural accuracy is tightly coupled to the operator's personal experience and manual dexterity. In complex anatomies, such as bifurcated coronary lesions, the difficulty escalates sharply, demanding exceptional technical skill and extensive clinical exposure to maintain safety margins. In addition, lengthy interventions test not only the surgeon's expertise but also physical endurance. Prolonged maintenance of a fixed posture induces muscular fatigue that progressively erodes both operative efficiency and technical quality.

2.2. Technological architecture and global development status of endovascular robotic systems

2.2.1. First-generation systems (2000–2010): Mechanically assisted era

The first generation of vascular interventional robots, represented by the U.S.-developed CorPath GRX, marked the transition from manual bedside manipulation to motorized mechanical assistance. These systems employed a single-axis drive to advance or retract the guidewire and catheter, offering only basic trajectory replication and position-holding capabilities [4]. However, they lacked force feedback, multi-degree-of-freedom control, and sub-millimetric precision, which limited their use to simple vascular lesions. As a result, clinical adoption remained below 10%.

2.2.2. Second-generation systems (2011–2020): Intelligent-control stage

The second generation introduced master-slave architectures, integrated force sensors, and provided remote, tremor-filtered manipulation. A representative platform is Siemens' RoboCor, which offered real-time force visualization and significantly improved the stability and safety of endovascular navigation [5]. These systems enabled combined push-pull and rotation of both guidewire and catheter, achieved force-feedback resolution around 0.2 N, and delivered sub-millimetric positional accuracy. Clinical studies reported procedural success rates exceeding 85% in complex coronary lesions, accompanied by > 90% reductions in operator radiation exposure.

2.2.3. Third-generation systems (2021–present): Convergence and innovation era

Current platforms integrate 5G-enabled remote operation, multimodal image fusion (e.g., X-ray,

IVUS, OCT), and AI-assisted path-planning algorithms, forming a closed-loop architecture of "precise sensing–intelligent decision–accurate execution." These advancements enable more autonomous navigation and enhanced real-time decision support. In preclinical large-animal studies, third-generation robots have already demonstrated the capability to precisely treat coronary bifurcations with diameters < 2 mm [6].

2.2.4. Global technology comparison

To illustrate differences in performance and system design across regions, **Table 1** summarizes the key technical specifications of domestic Chinese robotic systems compared with leading counterparts from the United States and Germany.

Table 1. Global comparison of key technical specifications in robotic systems

Technical specifications	Domestic robot (China)	International leading products (USA/ Germany)
Force-feedback resolution	0.1N	0.15N
Multimodal image-fusion latency	< 50ms	80–100ms
Remote-control network adaptability	5G / satellite dual-link	Dedicated network only
Instrument compatibility	Compatible with 95% of domestic instruments	Proprietary consumables only
Market price (USD 10,000)	80–100	150–200

Source: Global Vascular Interventional Robotics Industry Report 2024

3. Core technology innovations and breakthroughs

3.1. High-fidelity force-feedback system design

3.1.1. Sensor-array layout

The system adopts a hybrid sensing architecture that integrates distributed fiber Bragg grating (FBG) sensors with a six-axis force/torque transducer to achieve high-resolution, real-time perception of vascular interaction forces. A 32-channel FBG fiber embedded at the catheter tip provides approximately 10 μm spatial resolution, enabling precise detection of vessel-wall contact and subtle deformation patterns. Additionally, each robotic joint is equipped with an ATI Nano17 six-axis force sensor, offering a 500 Hz dynamic response and 0.01 N micro-force discrimination, thereby ensuring accurate measurement of multidirectional loads throughout the robotic transmission chain [7].

3.1.2. Haptic-force mapping algorithm

To achieve stable and perceptually accurate force rendering, an improved force-transmission model based on the Denavit-Hartenberg (D-H) kinematic framework was developed. The mapping between catheter-tip forces and operator-side haptic feedback is described by:

$$F_{human} = K \cdot (F_{tip} + C \cdot \dot{F}_{tip} + D \cdot \ddot{F}_{tip})$$

where $K = 0.8–1.2\ N\ mm^{-1}$ (self-adapting stiffness matrix), $C = 5\ N \cdot s\ mm^{-1}$ (damping), and $D = 0.5\ N \cdot s^2\ mm^{-1}$ (inertia)

MATLAB-Simulink verification shows haptic propagation latency < 20 ms and force error < 5 %.

3.1.3. Clinical-value validation

High-resolution force data acquired at the catheter tip are streamed to the master console in real time, giving surgeons an intuitive sense of instrument-vessel contact [8]. In 30 porcine coronary models, the force-feedback cohort exhibited a 3.2 ± 1.5 % endothelial injury rate versus 12.7 ± 3.8 % in the no-feedback group ($P < 0.05$), while device-to-target time fell by 23 %. Bench tests confirm a ± 0.1 N sensing error band; *in vivo* data demonstrate significantly improved procedural accuracy and marked reduction in vascular trauma [9].

3.2. Ultra-precision master-slave control technology

The master-slave control module enables micron-level guidewire advancement by coupling high-precision mechanical kinematics with coordinated electromagnetic actuation. The operational workflow consists of three core components:

(1) Instrument coupling: The introducer sheath is first inserted into the common femoral artery, after which a pre-curved guidewire is advanced through the sheath to the target lesion (e.g., aortic stenosis). Controlled rotation of the guidewire enables selective entry into vascular branches. A coiled stent is pre-mounted on the same guidewire and propelled by a dedicated pusher-wire whose distal tip incorporates a bifurcated notch to securely engage the stent [10];

(2) Electromagnetic actuation unit: The motion of the guidewire is governed by a pair of electromagnets: left electromagnet A, responsible for clamping and releasing, and right electromagnet B, which performs clamping, releasing, and translational movement along a linear slide. Advancement is achieved through an alternate clamp-slide cycle, consisting of:

(i) A releases;

(ii) B clamps and slides left, advancing the wire;

(iii) A re-clamps;

(iv) B releases and slides right, resetting without causing wire retraction.

Repeated cycles generate incremental, step-wise forward motion with micron-scale precision [11].

(3) Channel design: A three-port manifold consolidates the guidewire (port 1) and pusher-wire (port 2) into a shared output lumen (port 3) connected to the introducer sheath. This configuration enables fully integrated delivery of both components, eliminating the need for sequential manual instrument exchanges during the procedure.

3.3. Multi-modal image-fusion navigation

By co-registering X-ray, CT and MRI data, the system provides comprehensive intra-operative visual support. Key innovations are heterogeneous image registration and augmented-reality (AR) visualization [12].

3.3.1. Heterogeneous registration

A “feature-point + elastic warp” pipeline extracts bony landmarks from X-ray angiography (XRA) and the 3D vascular skeleton from CTA, then builds a B-spline deformation field for rigid/non-rigid alignment. Target registration error < 0.8 mm.

3.3.2. AR visualization

A Unity3D-based navigator fuses live XRA with pre-operative CTA, where its functions are as follows:

(1) AI auto-tagging of lesions (94 % accuracy);

(2) Dynamic path planning: Red = high-risk, green = recommended trajectory [13].

3.3.3. Clinical impact

In 50 complex aneurysm embolizations, fusion navigation reduced targeting time to 3.2 ± 0.8 min vs 5.7 ± 1.2 min for XRA alone ($P < 0.05$) and cut coil-packing error by 35 %.

4. Clinical implementation and evidence

4.1. Multi-centre RCT design

4.1.1. Protocol

A prospective, multicentre, randomized controlled trial was conducted across 10 tertiary medical centres, enrolling a total of 300 patients. Participants were randomly assigned in a 1:1 ratio to either the robot-assisted intervention group (n = 150) or the conventional manual intervention group (n = 150).

The primary endpoint was the incidence of 30-day major adverse cardiovascular events (MACE) [14]. Secondary endpoints included air-kerma radiation dose, procedure duration, number of device repositioning attempts, and contrast volume used [15].

4.1.2 Inclusion criteria

The inclusion criteria are as follows:

(1) Lesions: left-main or CTO;

(2) Age 18–80;

(3) ECOG ≤ 2;

(4) Written informed consent.

4.2. Results

4.2.1. Safety & efficiency (n = 100 pilot)

In the initial pilot cohort of 100 patients, the robot-assisted system demonstrated notable improvements in procedural efficiency and manipulation accuracy. The mean procedure time was significantly shorter in the robotic group compared with conventional manual operation (45 min vs 65 min). Precision of guidewire and catheter manipulation was also enhanced, with mean positional error reduced to 0.5 mm in the robotic arm versus 1.2 mm in the manual arm. Overall complication rates were lower in the robotic group (5% vs 15%).

In the subsequent randomized controlled trial (RCT), the incidence of 30-day MACE was 4.7% in the robotic arm compared with 9.3% in the manual group (RR 0.50; 95% CI 0.23–0.89; p = 0.02). This reduction was primarily attributable to lower rates of vessel perforation (0.7% vs 3.3%) and dissection (2.0% vs 5.3%).

4.2.2. Radiation protection

Robotic operation resulted in substantial reductions in operator radiation exposure. Mean operator dose was 0.32 ± 0.11 mSv in the robotic group, compared with 1.15 ± 0.34 mSv under conventional practice, representing a 72% reduction.

Correlation analyses revealed that radiation dose in the robotic arm was weakly associated with procedure duration (r = 0.21, $P > 0.05$), whereas dose in the conventional group showed a strong positive correlation with time (r = 0.83, $P < 0.01$), indicating consistent radiation burden with prolonged manual fluoroscopy use.

4.2.3. Cost-effectiveness

Despite high capital cost, break-even occurs at > 200 cases/year through: 25 % contrast saving, 40 % wire loss reduction, LOS 5.2 d vs 6.8 d [16].

5. Challenges and future directions

5.1. Current bottlenecks

5.1.1. Vascular dynamics

Pulsatile blood flow (peak velocity ≈ 50 $cm \cdot s^{-1}$) and vessel-wall elasticity spanning E = 0.5–10 MPa introduce nonlinear deformation that attenuates force-feedback accuracy by 15–20%. These hemodynamic factors complicate real-time sensing and make high-fidelity haptics difficult to maintain. Future systems will require adaptive, flow-model-based control algorithms capable of compensating for dynamic vascular loading.

5.1.2. Device compatibility

Current robotic end-effectors show limited compatibility with microcatheters below 1.5 mm in outer diameter (e.g., Echelon-10), restricting use in neurovascular and distal-peripheral interventions. A redesign supporting the full 2–8 Fr device range is essential to enable comprehensive multi-specialty applicability.

5.1.3. AI decision lag

AI-assisted navigation is constrained by reliance on static preoperative imaging, which cannot reflect intraprocedural changes such as plaque rupture, thrombus migration, or abrupt lumen collapse. Integration of real-time IVUS/OCT data, combined with reinforcement-learning algorithms, is needed to achieve rapid, context-aware decision-making.

5.2. Emerging frontiers

5.2.1. Bio-integrated robotics

Next-generation systems aim to merge biodegradable stent technologies with robotized *in situ* drug delivery, enabling targeted therapy with reduced restenosis and enhanced vessel healing.

5.2.2. Remote networked intervention

The advent of 6G communication with <10 ms end-to-end latency may enable “hub-county-home” hierarchical tele-intervention models. Such systems could reduce rural cardiovascular emergency response times by over 40%, significantly improving equity of care.

5.2.3. Human-robot symbiosis

Brain-computer interface (BCI) modules capable of decoding EEG-based operator intent represent a new paradigm of “thought-to-robot” interaction. Early projections suggest up to a 30% increase in decision and response speed, supporting semi-autonomous operation in complex anatomical environments [17].

6. Policy recommendations

To accelerate translation and responsible deployment of endovascular robotic technologies, the following policy

actions are proposed:

(1) Establish national centres of excellence dedicated to robotic vascular intervention, serving as hubs for training, standardization, and high-level research [18];
(2) Incorporate robotic procedures into medical reimbursement systems, and pilot flexible financing models such as "lease-plus-per-case" payment to support hospital adoption;
(3) Strengthen academia-industry-hospital consortia to create an integrated innovation pathway spanning basic research, engineering development, and clinical validation, ensuring sustainable technological advancement.

7. Conclusion

Vascular interventional surgical robots are redefining the landscape of minimally invasive cardiovascular therapy through breakthroughs in sensing, control, and imaging intelligence. The system developed by Xu's team exemplifies this progress, achieving high-fidelity force feedback, micron-level master-slave manipulation, and advanced multimodal image-fusion guidance. Comparative analyses show that its performance meets or surpasses leading international platforms, while multicentre clinical evidence demonstrates meaningful gains in safety, precision, and radiation protection. Despite persistent challenges, including vascular dynamic modeling, device compatibility, and real-time AI decision-making, the trajectory of innovation points toward increasingly autonomous, networked, and patient-specific robotic interventions. Continued integration of advanced materials, next-generation communication networks, and human-robot interaction technologies will further accelerate clinical adoption. Ultimately, the maturation of these systems is expected to enhance therapeutic outcomes, reduce occupational risks, and establish a new standard of care in endovascular medicine.

Disclosure statement

The author declares no conflict of interest.

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