EDITORIAL

Robot-assisted carotid stenting: Precision, ergonomics, and the next frontier in vascular surgery

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THE RATIONALE FOR ROBOTIC CAROTID INTERVENTION

Carotid artery stenting (CAS) remains among the most technically demanding endovascular procedures, requiring submillimetric precision in a restricted anatomic zone essential to cerebral blood flow. The introduction of endovascular robotic systems offers a potential transformation in both procedural accuracy and operator safety. Although robotics has seen growing clinical application in coronary and peripheral interventions, its application to carotid revascularization holds great potential.

The foundation of vascular robotics was established more than a decade ago, when the technical feasibility of robot-assisted endovascular navigation using the Magellan (Hansen Medical) and CorPath (Siemens Healthineers) systems was first demonstrated.[1] This work introduced the core principles of motion scaling, tremor elimination, and radiation protection that underpin the potential benefit of embracing robotics in endovascular practice. Subsequent studies from the same group, including quantitative motion analyses by Lettenberger and Legeza,[2,3] provided an objective framework for measuring operator precision during simulated CAS and transformed robotics from conceptual novelty to a quantifiable discipline of motion-based performance.

The evolution of "digital surgery," integrating robotics, imaging, data analytics, and artificial intelligence, is beginning to redefine procedural precision and feedback loops across surgical disciplines. As recently highlighted in *J Vasc Surg*, robotics represents a core element of this transformation, enabling procedural movements to be recorded, analyzed, and optimized to improve accuracy and training while reducing variability across operators. This integration of computing and performance analytics situates robotic carotid intervention within the broader framework of digital surgery.[4]

Because of the increase in endovascular procedures, vascular specialists are increasingly confronted with the cumulative effects of ionizing radiation and ergonomic strain from lead aprons during fluoroscopy-guided interventions. Chronic exposure, coupled with the physical burden of lead aprons, contributes to operator fatigue and musculoskeletal injury while raising long-term oncologic concerns.[5,6] Robotic systems help mitigate these occupational hazards by allowing manipulation of standard wires and catheters from a shielded remote workstation, effectively eliminating radiation exposure to the operator. At the carotid bifurcation, where even subtle catheter instability can dislodge plaque and cause cerebral embolization, robotic motion scaling (eliminating tremor and descaling motion if desired) and device locking (stabilizing catheters or wires) may directly enhance procedural safety.

CURRENT EVIDENCE AND CLINICAL EXPERIENCE

Carotid-specific evidence for robotic systems, although limited, is steadily increasing. In an ex vivo simulator, Legeza et al[3] compared manual and robotic CAS and found significantly smoother motion with robotic manipulation, reflected by lower spectral arc length (a quantitative measure of movement smoothness; -8.63 ± 3.98 vs -5.78 ± 3.14; $P = .04$) and greater idle time (the proportion of time the instrument tip remains stationary; 8.9 ± 8.7 seconds vs 3.5 ± 3.9 seconds; $P = .02$). Lettenberger et al[2] confirmed these results, reporting smoother guidewire motion and reduced velocity variability under robotic control. Together, these studies demonstrate that robotic assistance enables more deliberate stable control, albeit with modestly longer procedure times.

Clinical evidence, although limited, supports these experimental findings. Weinberg et al[7] reported six robotic CAS procedures performed using the CorPath GRX system, all technically successful and without periprocedural stroke or access-site complications. The procedure duration was longer than with manual cases (85 vs 61 minutes; $P = .023$), consistent with early learning-

curve effects, whereas fluoroscopy times were similar. Roy et al[8] analyzed 360 robotic and manual neuroendovascular procedures, including a subset of CAS, and reported similar complication rates and radiation exposure, although robotic cases required longer duration. A broader systematic review of robotic neurointerventional procedures, including both carotid and intracranial interventions, also found pooled technical and clinical success rates comparable to conventional approaches.[9] A recent systematic review by Łajczak et al[10] further highlighted both the technical feasibility and the potential risks of robotic carotid and neuroendovascular interventions, emphasizing the need for careful patient selection, awareness of device limitations, and prospective evaluation of neurological outcomes.

The proximity of the carotid bifurcation to the cerebral circulation underscores the importance of precise motion control, as small emboli can cause neurological events. Tremor elimination and motion scaling directly address this risk, whereas programmable device motion may help standardize procedures across operators and institutions. Quantifying catheter movement also enables the development of measurable skill benchmarks and simulation-based training for carotid intervention. Robotic procedures showed smoother and more stable motion, suggesting reduced fine motor strain.[2,3] Beyond operator-controlled motion, patient-related factors such as involuntary movement and anesthesia strategy may also influence procedural reproducibility. Patient motion represents a potential concern during any endovascular intervention; however, its impact on robotic-assisted CAS appears comparable to that of manual procedures. Current robotic systems operate on standard endovascular platforms using conventional guidewires and catheters, meaning that patient movement is transmitted similarly in both approaches.[7,8] Importantly, robotic motion scaling and device locking may partially mitigate the effect of subtle involuntary patient movement by stabilizing catheter position during critical steps.[2,3] Most reported robotic CAS procedures have been performed under local anesthesia with conscious sedation, consistent with standard CAS practice, and general anesthesia is not a prerequisite for reproducible robotic performance.[7] Nevertheless, careful patient selection and communication remain essential, particularly during early adoption and in anatomically complex cases.

Among the main motivations for adopting robotic systems are their ergonomic and occupational advantages. Remote operation removes the operator from the radiation field and allows a seated posture without the physical burden of lead protection. Although direct ergonomic measurements remain limited, the potential benefits for operator health and occupational sustainability are considerable. Because musculoskeletal

symptoms affect up to three-quarters of endovascular practitioners, robotic systems may help improve workplace safety and reduce cumulative physical injury.

Despite these benefits, several limitations persist. Current systems lack true haptic feedback, limiting tactile perception of vessel resistance and device interaction. Partial manual assistance is still required for certain procedural steps, including the usage of interventional devices, and system setup adds approximately 15 to 20 minutes, reducing feasibility in acute or emergent settings. Costs remain substantial, encompassing both capital equipment and disposable components, and integration into existing workflow requires additional personnel training and logistical adjustments. The learning curve can be considerable, particularly for operators accustomed to direct manual control. Long-term outcomes, including restenosis, ipsilateral stroke, and neurocognitive effects, have not yet been assessed in prospective trials. For now, robotic CAS should be regarded as an adjunctive tool that improves precision and operator safety but does not yet replace manual expertise.

FUTURE PERSPECTIVES AND CLINICAL IMPLICATIONS

Endovascular robotic technology continues to advance rapidly. The Magellan CorPath GRX platforms demonstrated early feasibility and have achieved high procedural success with substantial reductions in operator radiation exposure. Longer operating times partly reflect that certain steps, such as balloon inflation and stent deployment, remain manual. Ongoing advancements in endovascular robotics are aiming to address these limitations. Robotic carotid stenting will also benefit from the growing investment in remote stroke intervention. Mechanical thrombectomy for acute ischemic stroke has proven highly cost-effective, yet remains limited by a shortage of neurointerventionalists, particularly outside major centers. As teleoperated robotic systems are developed for remote stroke treatment, opportunities for robotic carotid revascularization will expand in parallel, especially as many stroke patients also present with carotid stenosis requiring treatment. In the United States, transcarotid artery revascularization has rapidly evolved as a stroke-sparing alternative to transfemoral CAS by avoiding navigation across the diseased aortic arch. This concept has now been extended to transcarotid robotic access, as recently demonstrated in a cadaveric proof-of-concept study, demonstrating the technical feasibility of remote or semiautonomous carotid intervention.[11]

In June 2025, the first fully robotic remote endovascular stroke thrombectomy was performed between operators in Kaunas, Lithuania, and an experimental site in Paris, France, separated by more than 1600 km.[12] Three months later, the SENTANTE Stroke System (UAB

Inovatyvi Medicina) received U.S. Food and Drug Administration Breakthrough Device designation for its potential to enable remote neurothrombectomy in hospitals without on-site specialists. These developments illustrate the rapid progress in teleoperated and networked endovascular technology. Although primarily focused on intracranial intervention, such advances may eventually allow remote performance of carotid stenting in selected settings. In parallel, the neurointerventional field is undergoing rapid diversification, with at least half a dozen new startups developing next-generation robotic platforms for remote or semiautonomous neurovascular procedures. Although these systems are still in early development, their emergence underscores the accelerating innovation ecosystem surrounding endovascular robotics.

Early proof-of-concept studies have also demonstrated autonomous robotic navigation using fused imaging and preplanned "centerline" pathways, a sequence of XYZ coordinates that can be imported into robotic software to guide endovascular instruments. Integration of image fusion and electromagnetic tracking brings automation to endovascular navigation, moving toward the goal of semiautonomous or "assisted" robotic performance, with the possibility of centerline or "off-the-wall" navigation of endovascular devices.[13]

Future investigations should determine whether robotic stability reduces cerebral embolic load compared with manual CAS or transcarotid approaches and whether benefits differ by anatomical configuration. Integration with flow-reversal systems and neuroprotective devices warrants study, as does the quantification of learning curves using motion-metric analytics. Multicenter clinical trials are essential to evaluate long-term patency, neurological outcomes, and cost-effectiveness.

Robot-assisted CAS has progressed from conceptual innovation to early clinical application. Available data demonstrate procedural safety, ergonomic benefit, and consistent potential to enhance precision. As robotic systems evolve to incorporate force-sensing feedback, image fusion, and semiautonomous guidance, their role in carotid revascularization will likely expand. Rather than replacing manual expertise, robotics should be regarded as an extension that improves procedural precision and occupational safety, and enables remote operation in underserved areas. The carotid bifurcation provides an ideal setting to evaluate these technologies and may guide their broader adoption in endovascular practice.

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