Modeling Robotic-Assisted Mechanical Thrombectomy Procedure with the CorPath GRX Robot—the Core-Flow Study

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ABSTRACT

Background and purpose

Endovascular robotic devices may enable experienced neuro-interventionalists to remotely perform endovascular thrombectomy (EVT). This study aims to assess the feasibility, safety, and efficacy of robot-assisted EVT compared to manual procedures by operators with varying levels of experience, using a three-dimensional (3D) printed neurovascular model.

Materials and methods

M1-middle cerebral artery (MCA) occlusions were simulated in a 3D printed neurovascular model, linked to a CorPath GRX robot in a biplane angiography suite. Four interventionalists performed manual EVT (MA-EVT, n=45) and robot-assisted endovascular thrombectomy (RA-EVT, n=37) procedures. The outcomes included first-pass recanalization (TICI 2c-3), the number and size of generated distal emboli, and procedural length.

Results

A total of 82 experimental EVTs were conducted. A non-significant trend favoring the RA-EVT was observed in terms of final recanalization (89.2% versus MA-EVT 71.1%; p=0.083). There were no differences in total emboli count (16.54±15.15 versus 15.16±16.43; p=0.303). However, a higher count of emboli > 1mm was observed in the RA-EVT group (1.08±1.00 versus 0.49±0.84; p=0.001) compared to MA-EVT. The mean procedural length was longer in RA-EVT (6.43±1.71 minutes versus 3.98±1.84 minutes; p<0.001). Among established neurointerventionalists, previous experience with robotic procedures did not influence recanalization (95.8% were considered experienced; 76.9% were considered novice; p=0.225).

Conclusions

In a 3D printed neurovascular model, RA-EVT has the potential to achieve recanalization rates comparable to MA-EVT within competitive procedural times. Optimization of the procedural setup is still required before implementation in clinical practice.

Abbreviations

3D = three-dimensional; EVT = endovascular thrombectomy; MA = manual; MCA = middle cerebral artery; RA = robot-assisted

INTRODUCTION

Mechanical thrombectomy (MT) is the most effective treatment for acute ischemic stroke due to large vessel occlusion when combined with intravenous tissue plasminogen activator (IV-tPA), unless contraindicated, and is currently strongly recommended by all therapeutic guidelines.[1, 2] However, logistical and geographical limitations in the availability of rapid performance of the thrombectomy procedure create geographic inequities between territories due to being more accessible in urban areas than in remote rural locations that are distant from major cities.[2-4] Appropriate MT programs require not only modern angiography suites, but also certified physicians who are well-trained in neurointerventional procedures and remain in continual contact with the neuroscientific society; this ensures the highest quality standards. In recent years, endovascular robotic devices have emerged as a revolutionary technology that may transform the field of neurointerventional treatments.

The CorPath GRX System is the first FDA-cleared and CE Marked medical device for percutaneous coronary and vascular procedures. It utilizes articulated robotic arms with multiple degrees of freedom to handle micro guidewires and microcatheters, enabling submillimeter movements of both devices to perform precise neurovascular interventions. Physicians can control it remotely, reducing radiation exposure and providing a comfortable and more precise working distance.[5-7]

Studies focusing on the embolization of intracranial aneurysms have been published dating back to the first-in-human experience reported in 2018, in which a transradial diagnostic coronary angiography was performed.[6-7]

The potential use of robotic treatment in stroke thrombectomy procedures could represent a significant advancement in stroke treatment, providing an alternative solution for patients in non-urban areas. Robot-assisted endovascular thrombectomy (RA-EVT) could save time by avoiding long transfers; it also offers patients the possibility of being treated remotely by highly-skilled

neurointerventionalists, ultimately improving patient outcomes and quality of life. Although the CorPath GRX, which is capable of performing biaxial procedures, is not fully optimized for thrombectomy procedures, it allows multiple catheter maneuvers and yields an accuracy comparable—or superior—to manual procedures.

The present study aims to describe a potential setup and explore the feasibility (reaching the occlusion), safety (distal embolization), and efficacy (recanalization) of RA-EVT. This is compared to manual procedures performed by operators with varying levels of experience in robotics, using a 3D printed neurovascular model.

MATERIALS AND METHODS

Study design

Two neurointerventionalists with over three years of clinical experience in robotic-assisted neuroendovascular embolizations (i.e., robot-experienced) performed both manual EVT (MA-EVT, n=18) and RA-EVT (n=24). One experienced neurointerventionalist, in training for robotic procedure (i.e., robot-novice), performed both MA-EVT (n=6) and RA-EVT (n=13) procedures. Due to the exploratory nature of this pilot feasibility study, the total number of experiments performed by each interventionalist was not predefined based on efficacy assumption; a total number between 19 to 21 experiments per operator was decided.

Neurovascular flow loop model

The neurovascular model was based on the vascular anatomies extracted from anonymized CTA images. The manufacturing procedure comprises the following steps: medical image segmentation to generate the preliminary three-dimensional (3D) geometry of the vascular anatomy; mesh modeling

to simplify the anatomy and prepare a printable model; 3D printing setting; post-printing processing; and assembly.

Data in DICOM format was imported and loaded in 3D Slicer,[8, 9] where opacity threshold segmentation was performed to obtain the preliminary 3D geometry of the model. The preliminary 3D geometry was exported to Autodesk Meshmixer[10] for the modeling stage and exported to PreForm (Formlabs, Inc., Somerville, MA, USA) to configure the printing material, resolution, optimal geometry orientation, and support structure for 3D printing. The model was printed with commercially available photopolymer resin Elastic 50A at a resolution of 100 μm with a Form 3 SLA printer (Formlabs, Inc., Somerville, MA, USA). The post-printing process consisted of removing support structures from the model, a ten-minute dip in isopropyl alcohol, and exposure to 305 nm ultraviolet (UV) light at a temperature of 60° C for ten minutes. After the post-processing, the model parts were ensembled to constitute the final version of the neurovascular model, which includes the aortic arch, bilateral carotid arteries, middle cerebral arteries (MCAs) (up to two distal M2-MCA branches), anterior cerebral arteries (up to proximal A2), anterior communicating artery, posterior communicating arteries, and posterior cerebral arteries (up to proximal P2-PCA segments).

The neurovascular model was connected in a flow-loop setup to mimic blood circulation. The experimental setup comprised a hydraulic pump recirculating saline solution at 800 mL/min, a 3D printed model, and a 100 μm filter at the outflow of the model to collect the periprocedural emboli. All elements were connected through a silicone tubing system. To simulate the transfemoral access, an 8 F sheath attached to a silicone tube was connected to the descending aorta. An inflow filter was added between the hydraulic pump and the neurovascular model to filter out the undesired particles introduced into the system by reused devices.

Experimental thrombectomy setup

The study was performed using Biplane Angiography (Clarity, Philips Healthcare, Netherlands); 2x4 mm (Radiopaque) clots analogs were made from porcine blood, as previously described,[11] and used to create arterial occlusions in a benchtop 3D-printed model (**Figure 1A**).[12]

The CorPath Robot, consisting of a control console and a robotic unit quipped with an extension arm that can hold a single-use cassette, was installed in the interventional neuroradiology section. The control console, enabling the operator to perform procedures comfortably while seated, was placed in the RX control room. The extension arm and robotic unit were positioned on the lateral side of the table in the angio-suite. A single-use cassette was loaded with a microcatheter and a balloon guide catheter, both of which were connected to the neurovascular model.

The robotic system is currently unable to perform catheterization of the aortic arch since it is limited to an advancement movement of 20 cm. An initial assessment of the optimal positioning of the different devices was performed. Due to the above-mentioned limited range of movement of the microcatheter when using the robot, the limiting factor in order to reach and cross the clot with the microcatheter is the initial position of the balloon guiding catheter in the internal carotid artery (ICA). We identified the lowest point in the ICA in which the tip of the balloon guide catheter should be manually positioned before initiating the RA-EVT for different occlusion locations (**Figure 2**), and decided to place it in vertical part of the petrous segment of the ICA. Given this limitation, RA-EVT was considered optimal for occlusions located in the ICA and in the M1 segment of the middle cerebral artery (MCA), and in any case beyond proximal M2 branches.

After clot embolization, experiments were allocated into one of the following treatment arms: (1) Robot Experienced/MA-EVT; (2) Robot Experienced/RA-EVT; (3) Robot novice/MA-EVT; (4) Robot novice/RA-EVT. A 6-French balloon guide catheter (BGC) (Gateway, Stryker, California) was manually advanced by an experienced specialist nurse to the level of the distal ICA, then a 0.021”

microcatheter (Phenom 21, Medtronic, California) was manually advanced to the level of the tip of the BGC. For RA-EVT procedures, the microcatheter and a 0.014" micro-guidewire (Synchro 2, Stryker, California) were then connected to the CorPath GRX robot by a trained assistant nurse; the neurointerventionalist could take control of the system from the console located in the control room outside the angio-suite (**Figure 1**).

The thrombectomy technique, manual and robot-assisted, consisted of navigating the microcatheter under fluoroscopy to the MCA in order to cross the clot and then deploy a 4x40 mm stent-retriever (SR: Solitaire X, Medtronic, California) from the M2 to the M1-segment of the MCA. After an embedding time of 1-2 minutes, the BGC was inflated, and the SR was retrieved into the BGC under proximal flow arrest and continuous pump aspiration (Penumbra, California) (**Figure 1C**). For RA-EVT device exchanges in the robotic system, balloon inflation/deflation and aspiration were performed upon the neurointerventionalists' indication, executed by an assistant nurse.

Each experiment consisted of a single pass per embolized clot. The primary outcome was first-pass recanalization (FPR=TICI 2c-3); the secondary was the characterization of the collected distal emboli after each experiment.[13] The duration of the mechanical thrombectomy procedure was defined as the moment when the neurointerventionalist first initiated control of the console and began maneuvering the microcatheter, until completion of the first pass.

Characterization of distal emboli

Characterization of generated distal emboli has been performed as previously described.[12] The distal segments of the neurovascular model have vessels as narrow as 1mm. Thus, most embolized particles would end up in the filter located at the outflow of the model. To analyze the emboli generated after each pass, an RBG image of the particles in the filter was captured with a high-resolution digital camera (IPEVO, Inc., Sunnyvale, CA, USA). Then, the RBG images were processed by an image

processing algorithm developed on MATLAB R2020a (MathWorks, Inc., Natick, MA, USA). The algorithm comprises two primary stages: (1) RGB image binarization, which involves highlighting the emboli ("1") and removing the background ("0") (**Figure 2**); and (2) quantification of the major-axis length of each particle, taking a circle of known dimensions as a reference. Additionally, the algorithm provides outputs such as the overall particle count, as well as the number of emboli larger than 1mm.

Statistical analysis

Results were expressed as mean±SD. Data were analyzed using the SciPy library from Python. Normality was tested with Shapiro-Wilk, and the Mann-Whitney U test was used to evaluate differences between RA-EVTs and MA-EVTs. Multiple subgroup analyses were performed to assess the safety and efficacy of the procedure between the four treatment arms using a Chi-Squared Test.

As a subgroup analysis, differences in different outcomes (i.e., final recanalization rate, number and dimension of emboli, and duration of the mechanical thrombectomy procedure) were compared between RA-EVT performed by a robot-experienced interventionalist and RA-EVT performed by a robot-novice neurointerventionalist, who all had the same level of experience in mechanical thrombectomy procedures (>10 years).

Statistical significance was concluded when $p<0.05$.

RESULTS

A total of 82 experimental EVTs were conducted: 37 RA-EVT and 45 MA-EVT. Each interventionalist performed between 19 to 21 experiments. There were no robotic system failures or incidences that required the technician to step in during the thrombectomy attempts.

Robot-assisted EVT versus manual EVT

Overall, when comparing all RA-EVTs (n=37) versus all MA-EVTs (n=45), non-significant trends were observed in terms of final recanalization rate in favor of RA-EVT: 89.2% versus MA-EVT: 71.1%; p=0.083. The distal emboli analysis revealed a similar mean total count of particles (RA-EVT: 16.54±15.15 versus MA-EVT: 15.16±16.43; p=0.303); however, a significantly higher number of emboli larger than 1mm in diameter was observed in the RA-EVT (1.08±1 versus 0.49±0.84; p=0.001). In addition, the mean RA-EVT procedural length was significantly longer (RA-EVT: 6.43±1.71 minutes versus MA-EVT: 3.98±1.84 minutes; p<0.001) (**Figure 3**).

Robot-experienced versus robot-novice interventionalists

To assess the impact of the operators' prior experience in the use of the robot, we compared outcomes in experiments performed by robot-experienced (n=24) and robot-novice (n=13) interventionalists **(Table 1)**. The observed recanalization rates were 95.8% among the robot-experienced interventionalist and 76.9% among the robot-novice interventionalist (p=0.225). No significant differences were observed in terms of total emboli count (p=0.065) or number of emboli larger than 1mm (p=0.488). However, procedural length was found to be slightly but significantly longer for robot-experienced (6.85 ±1.54 minutes) as compared to robot-novice neurointerventionalist (5.65 ± 1.80 minutes; p=0.041) **(Figure 4)**.

DISCUSSION

In this pilot study, we aimed to characterize the procedural setup and feasibility of performing mechanical thrombectomy with a robotic-assisted device using a 3D vascular model. We determined

that the current robotic features allow an adequate setup to perform RA-EVT in intracranial occlusions located up to the proximal segments on the M2-MCA branches using balloon guide catheters and a stent retriever. In order to do so, patient anatomy should allow navigation of the BGC up to the C2-C3 segments of the ICA. In these conditions, intracranial RA-EVT performed by physicians with different levels of expertise in the use of the robot were able to achieve similar recanalization rates compared to MA-EVT. Robotic-assisted EVT may not appear to provide a significant advantage on its own; however, the current results present opportunities for future scenarios where skilled neurointerventionalists could potentially perform the intracranial part of a mechanical thrombectomy remotely on patients located in distant centers without specialized interventionalists.

In our study, the mean procedural time was slightly higher in the robotic arm as compared to the manual procedure, particularly among physicians with experience in robotic procedures. However, in a potential scenario of remote RA-EVT, the absolute increase in the RA procedural time could be neglected if compared to the delays associated with transferring a patient to a comprehensive stroke center to receive EVT.

Furthermore, we aimed to test the safety of the procedure in terms of generation of distal emboli. Overall, our study showed that the total count of generated distal emboli is similar between RA-EVT and MA-EVT. However, we observed a significantly higher number of emboli larger than 1mm in the RA-EVT group, which deserves special attention. These results may have been influenced by the use of a 3D plastic model, as the friction coefficients between the clot/devices and the vessels are higher than those in human arteries. However, we cannot exclude the possibility that this high rate of clots larger than 1cm may be due to the operators' lack of experience with the robot, including performing a procedure in the absence of haptic feedback. Nevertheless, we believe that in the preliminary phases of developing a device, it is important to collect data on the physician's

performance with the device, as this may provide insights into its characteristics and help identify areas for improvement. We anticipate that both operator experience and device performance can be improved in the future.

A possible explanation may lie in the relative absence of compliance with the current version of the robotic system when pushing the microcatheters across the thrombus. During the manual procedures, the interventionalist can modulate the applied force to gradually advance the microcatheter, avoiding sudden tension releases of the system; however, this may be more challenging with RA-EVT. This phenomenon could also have been magnified by the increased vessel wall friction of the 3D models as compared to patient's arteries. However, robotic systems have the potential to include automatic compensation and adjustment systems with the ability to optimize microcatheter navigation through the occluding clots.

Interestingly, expert physicians in robot handling achieved results similar to those of physicians with limited robotic exposure (**Figure 4**), suggesting that spreading this new technology with short learning curves among neurointerventionalists may be relatively straightforward.

To ensure universal and timely endovascular treatment of stroke patients with large vessel occlusions, future developments of regional networks will likely consider performing a local MT by an interventionalist not dedicated to neuroendovascular procedures, or opting for a remote RA-EVT performed by skilled neurointerventionalists.

To our knowledge, this is the first study that explores the feasibility of robotic assistance in the intracranial part of the mechanical thrombectomy. Our results suggest that further adjustments will make implementation of this technology possible in assisting acute ischemic procedures in rural areas, thus massively reducing workflow times.

The current CorPath GRX technology still presents limitations that prevent the immediate application of the studied model into clinical practice: it is currently unable to perform the catheterization of the supra-aortic trunks and deliver the microcatheter up to the clot occlusion. Moreover, the main limitation is the limited range of motion and the impossibility to control triaxial catheter systems, which prevents the use of intermediate distal access catheters that provide support during microcatheter navigation and that allow distal aspiration.

Our pilot study aimed to provide a preliminary assessment of the feasibility of technology to assist in performing intracranial mechanical thrombectomy and to generate initial efficacy data. Our results are promising and represent a necessary step toward the implementation of robotics in mechanical thrombectomy procedures. In the future, integration of acquired vessel imaging, such as CTA or angiography, with the robotic system may enable the robot to recognize the anatomy and offer an assisted navigation in cases of challenging anatomy. Such development allowing a faster, more precise, and safer procedure may facilitate the expansion of an adoption of robotic procedures among less experienced operators, or for remote assistance in rural regions.

Limitations

Our study has several limitations. A limited number of operators participated in the study, which may have affected the comparability of the observed outcomes among the various study groups. However, the operators—each having a varying level of experience—conducted multiple experiments to simulate multiple scenarios. Another important limitation is the use of a single 3D printed model, which is a significant constraint due to its limited comparability with real patients. Despite the neurovascular model being internally coated with hydrophilic agents, the friction coefficients between the clot/devices and the vessels are generally higher than those observed in human arteries. This may partially explain the increased number and size of distal emboli observed in the RA-EVT

arm. Additionally, the model exhibits higher resistance to perforation than *in vivo* conditions, which hinders the assessment of such complications. Furthermore, a single 3D model was used precluding the wider evaluation according to anatomical variations. We concur with the importance of further exploring the use of robotics to support the catheterization of challenging anatomies in future studies with new iterations of the robotic devices.

CONCLUSIONS

In a 3D printed neurovascular model, RA-EVT has the potential to achieve recanalization rates comparable to MA-EVT within competitive procedural times. Optimization of the procedural setup is still required before implementation in clinical practice.

REFERENCES

1. Majoie CB, Cavalcante F, Gralla J, et al. Value of intravenous thrombolysis in endovascular treatment for large-vessel anterior circulation stroke: individual participant data meta-analysis of six randomised trials. Lancet 2023;402:965-974

2. Kamel H, Parikh NS, Chatterjee A, et al. Access to Mechanical Thrombectomy for Ischemic Stroke in the United States. Stroke 2021;52:2554-2561

3. Perez de la Ossa N, Abilleira S, Dorado L, et al. Access to Endovascular Treatment in Remote Areas: Analysis of the Reperfusion Treatment Registry of Catalonia. Stroke 2016;47:1381-1384

4. El Nawar R, Lapergue B, Piotin M, et al. Higher Annual Operator Volume Is Associated With Better Reperfusion Rates in Stroke Patients Treated by Mechanical Thrombectomy: The ETIS Registry. JACC Cardiovasc Interv 2019;12:385-391

5. Mahmud E, Schmid F, Kalmar P, et al. Feasibility and Safety of Robotic Peripheral Vascular Interventions: Results of the RAPID Trial. JACC Cardiovasc Interv 2016;9:2058-2064

6. Mendes Pereira V, Rice H, De Villiers L, et al. Evaluation of effectiveness and safety of the CorPath GRX robotic system in endovascular embolization procedures of cerebral aneurysms. J Neurointerv Surg 2023

7. Karas PJ, Lee JE, Frank TS, et al. Robotic-guided direct transtemporal embolization of an indirect carotid cavernous fistula. J Neurointerv Surg 2023;15:1122-1123

8. Kikinis R PSDaVKG. 3D Slicer: A Platform for Subject-Specific Image Analysis, Visualization, and Clinical Support. New York: Springer New York; 2014:277-289

9. SlicerSolutions. 3D Slicer 4.10.2. 2019

10. Autodesk. Autodesk MeshMixer 3.5. 2018

11. Kan I, Yuki I, Murayama Y, et al. A novel method of thrombus preparation for use in a swine model for evaluation of thrombectomy devices. AJNR Am J Neuroradiol 2010;31:1741-1743

12. Li J, Tiberi R, Canals P, et al. Double stent-retriever as the first-line approach in mechanical thrombectomy: a randomized in vitro evaluation. J Neurointerv Surg 2023

13. Li J, Tiberi R, Bhogal P, et al. Impact of stent-retriever tip design on distal embolization during mechanical thrombectomy: a randomized in vitro evaluation. J Neurointerv Surg 2023

Table 1: Subgroup analysis of outcomes for experiments performed by robot-experienced vs. robot-novice interventionalists

Group	MT Duration (minutes)	Total Count	Total Count of Emboli >1mm	Recanalization Rate
INR – Robot Expert (n=24)	6.85 ± 1.54	19.67 ± 17.22	1.08 ± 0.78	95.8%
INR – Robot Not Expert (n=13)	5.65 ± 1.80	10.77 ± 8.06	1.08 ± 1.38	76.9%
INR Manual EVT (n=21)	3.76 ± 1.58	16.67 ± 13.09	0.57 ± 0.93	71%
RA-EVT (n=37) vs. all MA-EVTs (n=45)	6.43±1.71 vs. 3.98±1.84; p<0.001	16.54±15.15 vs. 15.16±16.43; p=0.303	1.08±1 vs. 0.49±0.84; p=0.001	89.2% vs. 71.1%; p=0.083
Robot-experienced (n=24) vs. Robot-novice (n=13) INR	6.85±1.54 vs. 5.65±1.80; p=0.041	19.67±16.85 vs. 10.77±7.75; p=0.065	1.08±0.76 vs. 1.08±1.33; p=0.488	95.8% vs. 76.9%; p=0.225

EVT = endovascular thrombectomy; INR = interventional neuroradiologist; MA = manual; MT = mechanical thrombectomy; RA = robot-assisted

FIGURE LEGENDS

Figure 1: A benchtop 3D printed vascular model with a thrombus inside (A) was connected to a Corindus CorPath GRX Robot (B, arrowhead), and mechanical thrombectomy was performed using stent retrievers (C).

Figure 2: Experimental setup for robot-assisted and manual EVTs

Figure 3: Boxplot analysis shows the difference in median values of various outcomes of thrombectomy (such as recanalization rate, procedural length, and distal emboli generation) when comparing all robotic-EVT and all manual EVT.

Figure 4: Boxplot analysis shows the difference in median values of various outcomes of thrombectomy (such as recanalization rate, procedural length, and distal emboli generation) when comparing robotic-EVT performed by a robotic-experienced interventional neuroradiologist (INR) and robotic-EVT performed by a robot-novice INR.