ORIGINAL ARTICLE

Optimizing the Workflow of Superficial Temporal Artery Mapping in Extracranial-Intracranial Bypass Surgery Using Mixed Reality: A Proof-of-Concept Study

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■ BACKGROUND: **Doppler ultrasound is the standard for mapping the superficial temporal artery (STA) during extracranial-intracranial (EC-IC) bypass surgery. Mixed reality (MR) offers a novel alternative by providing patient-specific anatomic overlays to better visualize the STA. This study aims to validate MR-guided STA mapping as a reliable preoperative planning tool in EC-IC bypass to the middle cerebral artery.**

■ METHODS: **In this proof-of-concept study, 7 patients undergoing STA—middle cerebral artery bypass surgery were enrolled. Preoperative computed tomography angiograms were superimposed onto the patient using MEDIVIS SurgicalAR. Six standardized anatomic fiducial points were chosen for intraoperative registration. Five points along the parietal branch of the STA were annotated using MR and Doppler techniques. Point-to-point discrepancies between the MR and Doppler maps were analyzed, and map overlap was evaluated with computer vision techniques (OpenCV, Python). Significance was set at $P < 0.05$.**

■ RESULTS: **MR mapping of the STA was faster than Doppler mapping (11.3 ± 1.47 vs. 67.2 ± 17.6 seconds; $P = 0.001$). When considering the time to register, the overall time for MR mapping was similar to Doppler (79.2 ± 39.8 vs. 67.2 ± 17.6 seconds; $P = 0.78$). Notably, MR outperformed Doppler at the distal segments of the STA (2.71 ± 0.91 vs. 20.90 ± 8.46 seconds; $P < 0.001$). Overall, the MR and Doppler maps demonstrated comparable alignment, with an average deviation of 4.46 ± 2.64 mm along the entire course of the mapped vessel.**

■ CONCLUSIONS: **MR provides comparable STA mapping accuracy to Doppler while reducing the mapping time. These findings suggest that the planned incision is unlikely to differ, providing early evidence for the feasibility of MR-guided mapping for EC-IC bypass procedures.**

INTRODUCTION

Extracranial-intracranial (EC-IC) bypass surgery is a critical revascularization procedure for patients with complex cerebrovascular pathology.[1] Superficial temporal artery (STA)—middle cerebral artery (MCA) procedures can restore interruptions to anterior cerebral circulation from Moyamoya disease, aneurysms, and other ischemic conditions.[2] The success of EC-IC bypass procedures relies heavily on the precise identification and utilization of donor vessels. The identification and dissection of the parietal branch of the STA can be complicated by abnormal anatomy. Historically, STA identification was planned using palpation and visual inspection and ultimately achieved by broad open dissection.[3] While relying on standard anatomical landmarks informed incisions in early bypass surgery, this technique was inefficient and often led to unnecessary

Key words
- Bypass surgery
- Cerebrovascular neurosurgery
- Mixed reality
- Operative workflow

Abbreviations and Acronyms
CTA: Computed tomography angiography
CV: Computer vision
EC-IC: Extracranial-intracranial
ICG: Indocyanine green
MCA: Middle cerebral artery
MR: Mixed reality
STA: Superficial temporal artery

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Supplementary digital content available online.

Citation: World Neurosurg. (2025) 204:124562.
https://doi.org/10.1016/j.wneu.2025.124562

*Journal homepage: **www.journals.elsevier.com/world-neurosurgery***

*Available online: **www.sciencedirect.com***

tissue disruption. The introduction of Doppler ultrasonography provided a noninvasive means of assessing flow dynamics and vessel location; however, this was limited in vessels of diminutive caliber. To address the shortcomings of Doppler in precise spatial visualization, microscope-integrated near-infrared indocyanine green (ICG) videoangiography has been used to assess real-time flow dynamics.[4,5] However, ICG is limited to surface vessels, has a short imaging window, and slows perioperative workflow.[5]

Mixed reality (MR)—guided STA mapping offers a significant advantage in providing a detailed, high-resolution visualization of individual anatomy.[6,7] Overlaying preoperative vascular imaging onto the patient in real-time can help harvest donor vessels, appropriately tailor craniotomy incisions, and identify deep-recipient vessels.[6,8] Early studies using MR have reported qualitative benefits in enhanced visualization but have failed to quantitate these benefits.[6] As MR gains traction as a tool in the operating room, greater integration is hindered by the need to substantiate MR as equal or superior to a gold standard without compromising preoperative workflow.

Despite its promise, a standardized workflow for MR-guided STA mapping remains underdeveloped. To further understand the benefit of MR-guided STA mapping, this study aims to 1) evaluate the alignment of the MR-guided map compared to the traditional Doppler-guided map and 2) assess the efficacy of MR in terms of mapping time and workflow integration. By analyzing procedural efficiency and spatial congruence between MR-guided and Doppler-guided maps, we aim to define the role of MR-guided STA mapping as a reliable and reproducible preoperative planning tool in EC-IC bypass surgery.

METHODS

Study Cohort

Following Institutional Review Board approval of this prospective study, 7 patients undergoing STA-MCA bypass surgery for Moyamoya disease between January 2024 and December 2024 at a single academic quaternary care center were identified. Patients aged more than 18 years undergoing EC-IC bypass surgery with a patent donor STA visualized on preoperative angiography were enrolled in this study. Those who lacked a visible donor STA on computed tomography angiography (CTA) were excluded. Demographic characteristics including patient age, biological sex, side of the donor vessel, and etiology of Moyamoya disease were documented. Patients consented to the procedure and to the publication of their images shown here.

Workflow

The workflow of the experimental design is presented in **Figure 1**. Patients undergoing STA-MCA bypass surgery had their STA donor vessels mapped using both MR and Doppler techniques. MR-guided mapping was conducted by an experienced MR user with more than 25 cranial registrations, while the Doppler-guided mapping was conducted by a single cerebrovascular neurosurgeon with more than 10 years of experience.

For the MR arm of this study, a standardized mapping protocol was followed. For each patient, a preoperative CTA was obtained and uploaded into the MR guidance platform, SurgicalAR (MEDIVIS, New York, USA). Anatomic fiducial points were placed on the volumetric rendering of the CTA prior to registration. The 6 standard fiducials used were: nasion, nasal tip, ipsilateral medial canthus, ipsilateral lateral canthus, ipsilateral pinna, and ipsilateral tragus. These points were chosen for their replicability between patients, ease of visibility to the MR headset, Hololens 2 (Microsoft, Redmond, Washington, USA), error reduction, and placement for the operator, as previously described.[9,10] Intraoperatively, the patient was pinned and positioned with the head parallel to the floor with the operative side toward the ceiling.[11] A reference array was secured to the patient's forehead, and then the volumetric rendering was registered in standard fashion using point-to-point fiducial matching of the virtual and real landmarks.

Once registered, the hologram was superimposed onto the patient and windowed to highlight the STA. The MR user then mapped the STA using an MR pen localizer to mark 5 points along the parietal branch of the STA, from the zygoma to the superior temporal line, spaced ∼1 cm apart. A picture was taken of the MR-guided map with reference to a fixed ruler in the field, which was used to address image scaling differences across participants for post-hoc image analysis. The MR-guided map was subsequently erased using an alcohol prep pad to prepare the field for the Doppler control mapping. **Figure 2** presents a detailed workflow of the MR mapping process.

For the Doppler control arm of this study, the surgeon was blinded to the MR-guided maps and employed Doppler localization of the STA as per standard technique.[2,11] Like the MR arm, 5 points were marked from the zygoma to the superior temporal line ∼1 cm apart along the parietal branch of the STA. A picture was taken to identify the map, and then the incision was planned based on the Doppler-guided map.

Data Processing and Analysis

The alignment and spatial congruence between the MR and Doppler maps were analyzed using 2 methods: Euclidean distance between 3 distinct points (proximal, middle, and distal) along the course of the STA map and a computer vision (CV) analysis comparing the overlap between the 2 maps. The distances between points from the proximal, middle, and distal points along the STA map were measured for each patient.

Alignment of the MR maps to the in-situ vessel would have been ideal in theory; however, this was not a reliable measure due to tissue deformation during dissection, including soft tissue and vessel displacement. These changes significantly alter the orientation of the STA compared to preoperative angiograms, making direct comparison unreliable. Thus, alignment between the MR-guided and Doppler-guided maps was analyzed using advanced CV techniques. One such method, blob detection—a CV technique that identifies and analyzes regions in an image that differ in properties such as color, shape, and intensity—was applied to identify the annotated points on both maps for each patient (OpenCV, Python).[12,13] These points were standardized to a 5-mm diameter, approximating the diameter of the pen annotations on the skin surface for both MR and Doppler maps. The tragus for each patient served as a reference point to ensure proper orientation and standardization of images, while the ruler in the surgical field enabled consistent image scaling across participants. Points were connected in sequence using lines of uniform 5 mm

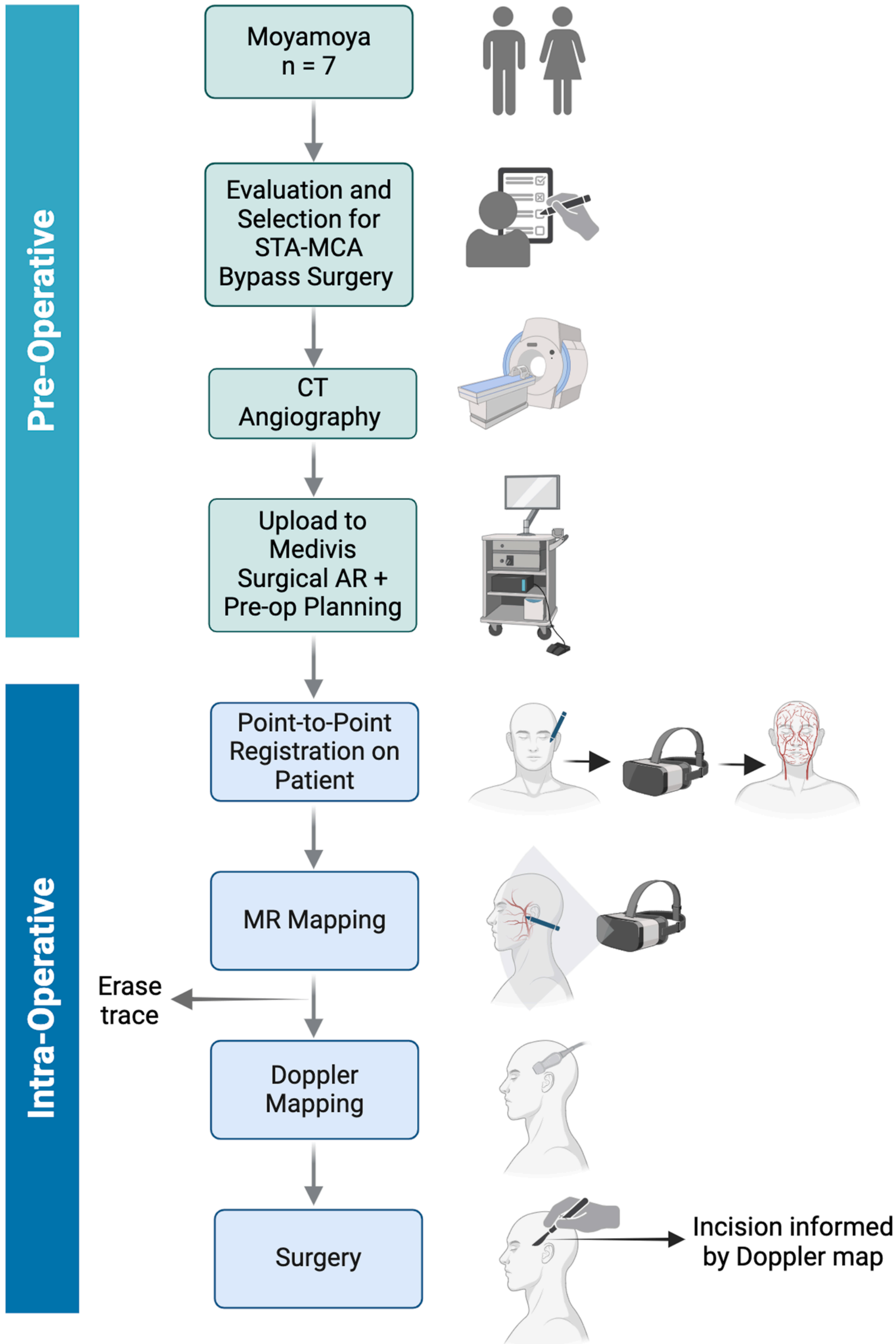

Figure 1. Study design. Seven patients with Moyamoya undergoing STA-MCA bypass surgery were identified. STA mapping was conducted for each patient, first using mixed reality (MR) and then Doppler. The Doppler map is ultimately used for operative planning. Figure was created using BioRender.com. STA, superficial temporal artery; MCA, middle cerebral artery.

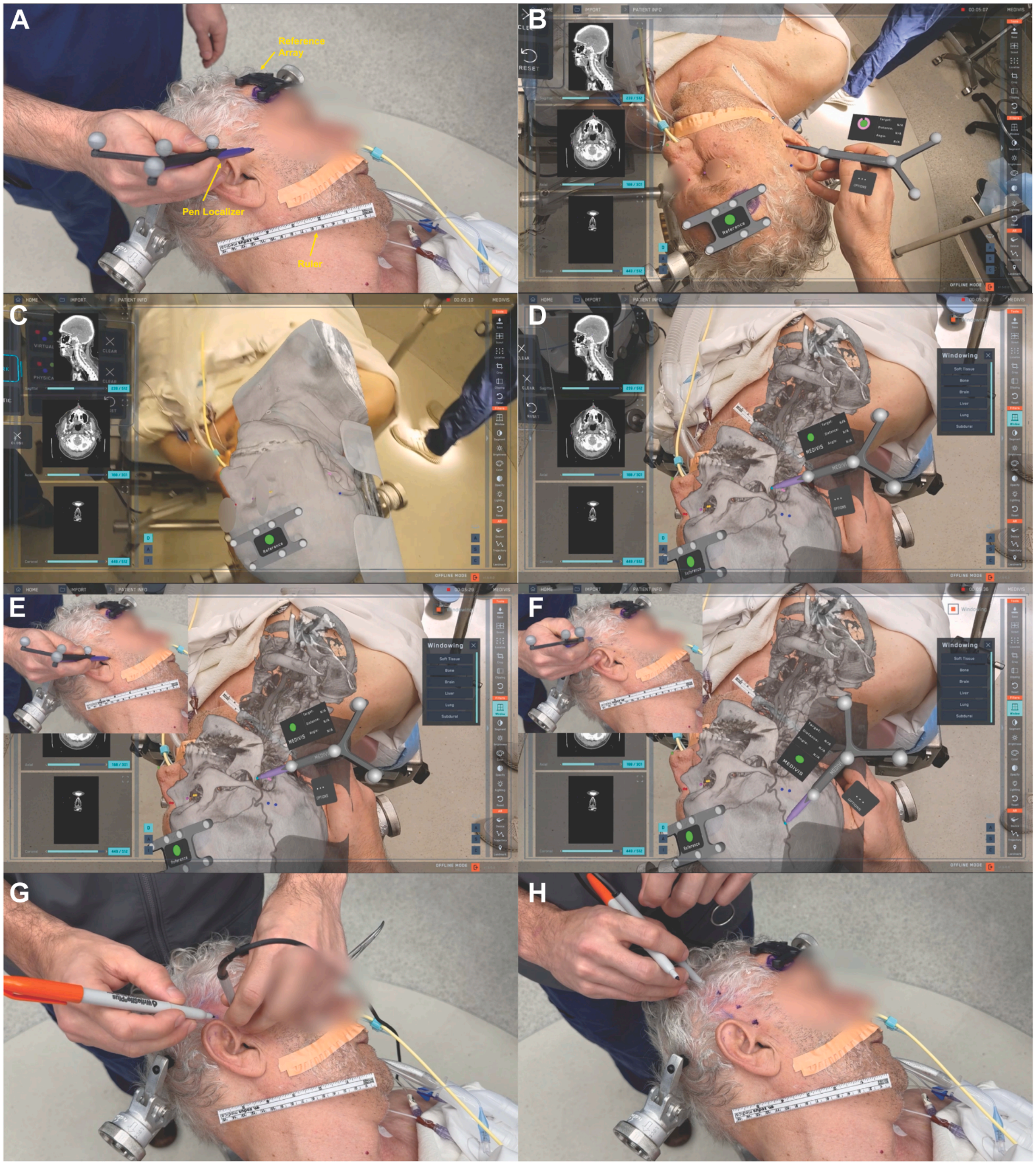

Figure 2. Experimental workflow using Patient 003 as an example. (**A**) MR setup; reference array is placed on patient's forehead for easy visualization during mapping procedure. A pen localizer is used to track the tool in holographic space during mapping. Ruler is used for post-hoc analysis to compare the MR and Doppler maps. (**B**) Registration is conducted using 6 anatomical fiducials: nasion, nasal tip, medial canthus, lateral canthus, pinna, and tragus. (**C**) Hologram is successfully registered onto patient. (**D**) Windowing field to the vasculature window. (**E**) Start of MR mapping. (**F**) End of MR mapping. (**G**) Start of Doppler mapping. (**H**) End of Doppler mapping. MR, mixed reality.

thickness, with blue representing MR mapping and red representing Doppler mapping. Pixel coordinates of the MR and Doppler maps were classified as the 'overlapping region' and were indicated in green. This was done using a modified version of Intersection over Union, a common technique for measuring the overlap of different systems for identifying objects in deep learning-based CV tasks.[14]

Distance analyses were performed to assess the difference between the MR and Doppler mapped lines. The Fréchet distance was obtained to determine the furthest distance that the 2 lines deviate. The area under the curve was calculated by getting the sum of the lengths of 500 evenly spaced perpendicular lines, across the MR and Doppler lines. The area under the curve was then normalized to get the average distance between the lines.

Timing was measured for both MR-guided and Doppler-guided maps; MR timing was subdivided into intraoperative registration plus mapping and isolated mapping. Timing was measured from the beginning to the end of each task. Registration and mapping times were compared using one-way analysis of variance and Mann-Whitney U statistical analysis (GraphPad Prism, Prism, San Diego, California, USA). Multiple unpaired t-tests were conducted for the point-to-point analysis. Significance was set for all analyses at $P < 0.05$.

RESULTS

Study Cohort

There were 7 patients who were diagnosed with Moyamoya and who underwent MR mapping of the STA for STA-MCA bypass surgery. Of the 7 patients, there were 4 females. Median age at presentation was 51 years (range: 31—83 years). Most patients (4/7) underwent left-sided STA grafting (Table 1).

Timing Analysis

Timing analyses were conducted for both MR and Doppler mapping. Overall, the combined time for MR registration and mapping was comparable to Doppler mapping (79.2 ± 39.8 vs. 67.2 ± 17.6 seconds; $P = 0.78$). However, when considering mapping times alone, MR was significantly faster than Doppler (11.3 ± 1.47 vs. 67.2 ± 17.6 seconds; $P = 0.001$) (Figure 3A).

A subanalysis was performed to evaluate MR's efficiency in mapping points along the course of the STA compared to Doppler. MR mapping demonstrated significantly faster times at distal segments of the STA. Specifically, MR was faster than Doppler mapping at point 3 (1.91 ± 0.62 vs. 10.0 ± 6.12 seconds; $P = 0.014$), point 4 (2.3 ± 0.52 vs. 19.00 ± 12.17 seconds; $P = 0.014$), and point 5 (2.71 ± 0.91 vs. 20.90 ± 8.46 seconds; $P < 0.001$) (Figure 3B).

Point-to-Point Discrepancy Analysis: Euclidean Distance

Euclidean distance was measured at the proximal, middle, and distal points along the path of the STA to evaluate the alignment of MR and Doppler maps. It was hypothesized that the point-to-point discrepancy would be lower and MR-Doppler congruence would be higher at the proximal points due to larger vessel diameter in this region. In contrast, greater point-to-point discrepancies were anticipated distally and thus reduced congruence between MR and Doppler maps, where vessel localization becomes more challenging due to diminishing vessel diameter. Across all 7 patients, the average point-to-point discrepancy at the proximal, middle, and distal points was 2.66 ± 1.25 mm, 3.71 ± 2.81 mm, and 4.98 ± 2.49 mm, respectively. Although the differences were not statistically significant, we observed a trend consistent with our expectations: proximal measurements had lower discrepancies compared to distal points (2.66 ± 1.25 mm vs. 4.98 ± 2.49 mm; $P = 0.17$) (Figure 3C).

Map Overlap Analysis: Computer Vision

A more robust analysis of mapping alignment was performed using CV techniques, as outlined in the workflow in Figure 4. CV analysis used the Laplacian of Gaussian blob detection technique to identify the 5 mapped points with MR and Doppler. Two independent methods were used to investigate the alignment between the MR and Doppler maps. The average Fréchet distance, which represents the maximum deviation between the 2 maps, was 10.42 ± 4.04 mm, while the average perpendicular distance across the entire length of each map was 4.46 ± 2.64 mm (Table 1, Figure 4E-F).

Table 1. Demographics and MR Mapping Metrics

Patient ID	Sex	Age	Laterality	Total Doppler Timing (seconds)	MR Registration Timing (seconds)	MR Mapping Timing (seconds)	MR Total Timing (seconds)	Frechet Distance (mm)	Average Perpendicular Distance (mm)
001	F	39	R	102.88	93.63	11.14	104.77	13.14	1.48
002	M	51	L	55.08	72.18	10.14	82.32	10.24	7.57
003	M	83	R	56.35	89.29	10.71	100	16.7	2.61
004	M	51	L	54.19	131.82	11.57	143.39	7.65	2.87
005	F	65	L	61.00	26.12	13.22	39.34	7.93	5.99
006	F	55	R	63.56	27.99	12.92	40.91	12.57	7.95
007	F	35	L	77.10	34.78	9.08	43.86	4.74	2.77

MR, mixed reality; F, female; R, right; M, male; L, left.

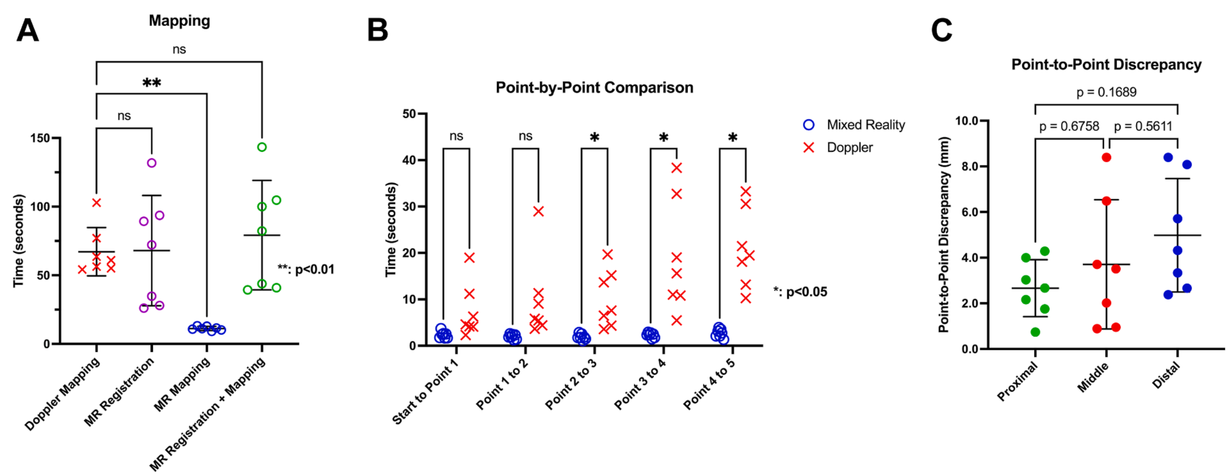

Figure 3. MR and Doppler mapping analysis. (**A**) Comparison of MR and Doppler mapping times shows that MR is significantly faster ($P < 0.01$); however, the overall times for Doppler and total MR are comparable. (**B**) Subgroup analysis of the timing for each individual mapped point highlights MR's superiority beginning at point 3 onwards, especially in the distal portions of the STA. (**C**) Point-to-point discrepancy analysis between the proximal, midpoint, and distal points of each map. MR, mixed reality; STA, superficial temporal artery.

DISCUSSION

The STA-MCA bypass is a well-established revascularization procedure for ischemic cerebrovascular conditions such as Moyamoya disease.[1] The early technique for STA identification was pioneered by Yasargil in the 1970s, relying on visual inspection, palpation, and open dissection as the primary methods for vessel localization.[3] Advancements in intraoperative imaging over the past decades, including Doppler ultrasonography and ICG videoangiography, have overcome the limitations of these conventional techniques by incorporating real-time flow dynamics for vessel mapping.[4] While these modalities provide valuable intraoperative guidance, they remain constrained to superficial vasculature and especially diminutive vasculature. In contrast, MR-based navigation is emerging as a powerful adjunct in STA-MCA bypass, as it can enable real-time visualization of patient-specific vascular anatomy.[6-8] Beyond facilitating superior intraoperative visualization of deep structures, MR has been shown to improve surgical workflow efficiency.[9,15] Traditional neuronavigation systems often require a large physical footprint and may interfere with bimanual microsurgical techniques by requiring the surgeon to look away from the operative field, especially when using handheld navigation tools.[15] MR-guided techniques facilitate frameless, real-time navigation through a streamlined headset and workstation, which aims to optimize intraoperative efficiency while preserving surgical ergonomics.

We found that MR mapping of isolated vessel identification was faster than traditional hand-held Doppler mapping. Notably, when evaluating the alignment of the MR and Doppler maps, we found that the average distance between the 2 lines was 4.46 mm, which is comparable to the typical diameter of the STA.[16] This concordance between the 2 maps suggests that the vessel localization using MR may be sufficiently accurate such that the resultant surgical incision would not change between either MR or Doppler modalities. These findings demonstrate the noninferiority of MR in point-to-point mapping accuracy, supporting its use as a reliable alternative to standard Doppler.

Despite the absolute difference in mapping time between MR and Doppler being measured in seconds, this difference may hold clinical significance in settings where Doppler fails to reliably detect vessels, particularly in distal segments and in vessels with diminutive caliber. In fact, this advantage was evident in an illustrative case with Patient 006 (**Figure 5**), where the utility of MR is highlighted. Notably, in this case, the distal-most points were difficult to localize using Doppler guidance, prompting the surgeon to request additional MR guidance to assist in identifying the distal and narrow segments of the STA. This resulted in 2 additional points being marked, which altered the trajectory of the Doppler map and provided additional input for incision planning (**Figure 5C-D**). This illustrative case demonstrates the utility of MR-guided techniques to influence surgical decision-making in real time and highlights its increasing efficiency in localizing distal, small caliber vessels, where Doppler mapping is traditionally limited.

Video

Video available at www.sciencedirect.com

In addition to mapping the STA, MR guidance enables intuitive, real-time visualization that can be used to localize intraoperative vessels and tailor craniotomy sites during the preoperative phase. **Video 1** illustrates a workflow that integrates MR to create a comprehensive preoperative plan for STA-MCA bypass cases. Here, the surgeon can register the patient, localize the STA, and then subsequently

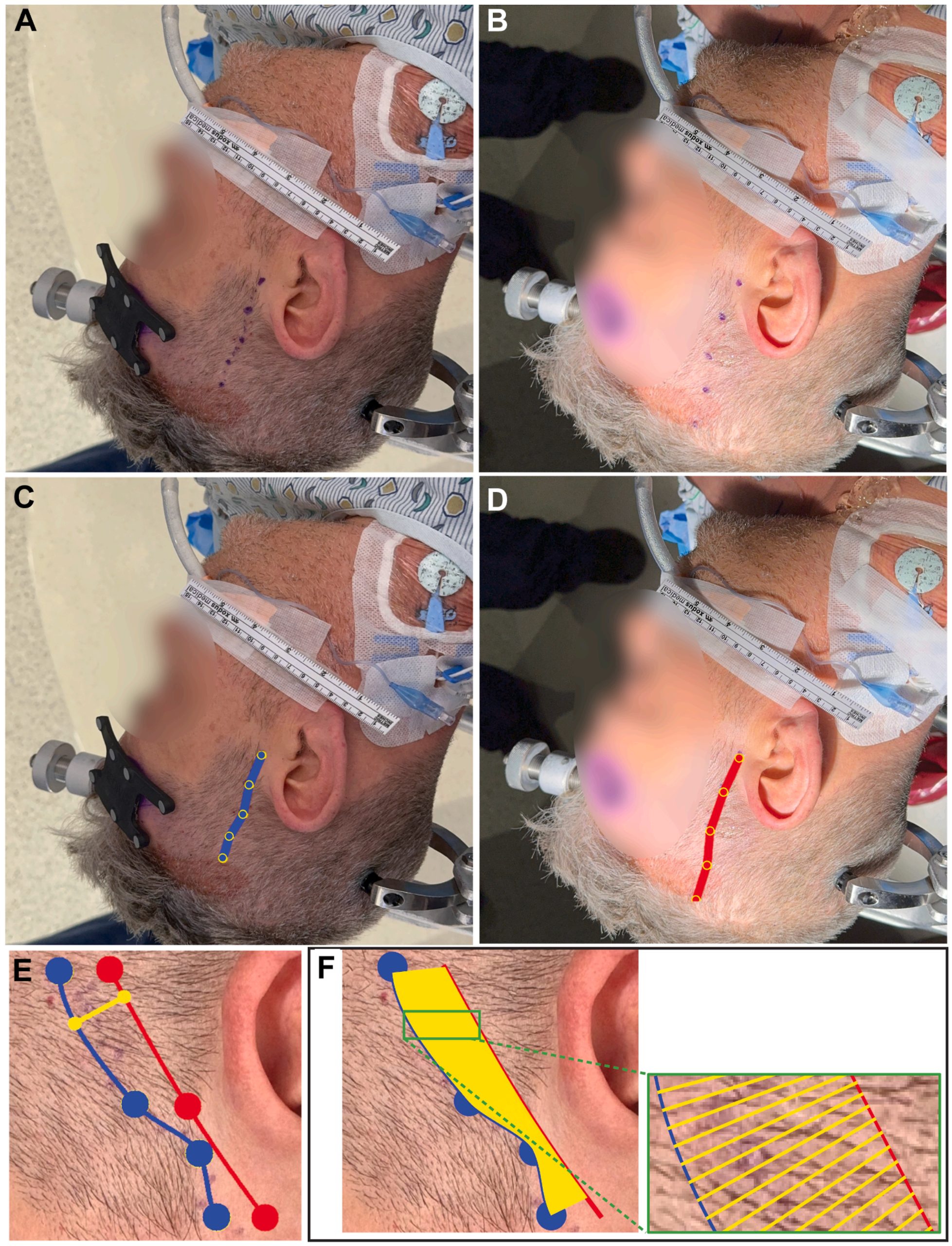

Figure 4. Alignment of the MR-guided maps using Doppler-guided maps as a reference using Patient 004 as an example. (**A**) MR-guided and (**B**) Doppler-guided maps. (**C**) Annotated MR and (**D**) Doppler maps using computer vision assuming a 5-mm thickness. (**E**) Overlay maps, with MR shown in blue and Doppler shown in red. The Fréchet distance is annotated in yellow for Patient 004 of 7.65 mm. (**F**) Example of the AUC analysis showing an average distance between each line of 2.87 mm. MR, mixed reality; AUC, area under the curve.

localize the MCA to precisely plan a craniotomy over the desired location. Beyond localization, the virtual assets of the patient also provide a unique opportunity to view aberrant anatomy in 3-dimensional space prior to incision which can make surgeries more personalized. The use of SurgicalAR in this study was constrained by its current Food and Drug Administration approval status, which is limited to preoperative planning for cranial cases. As a result, intraoperative confirmation of vessel

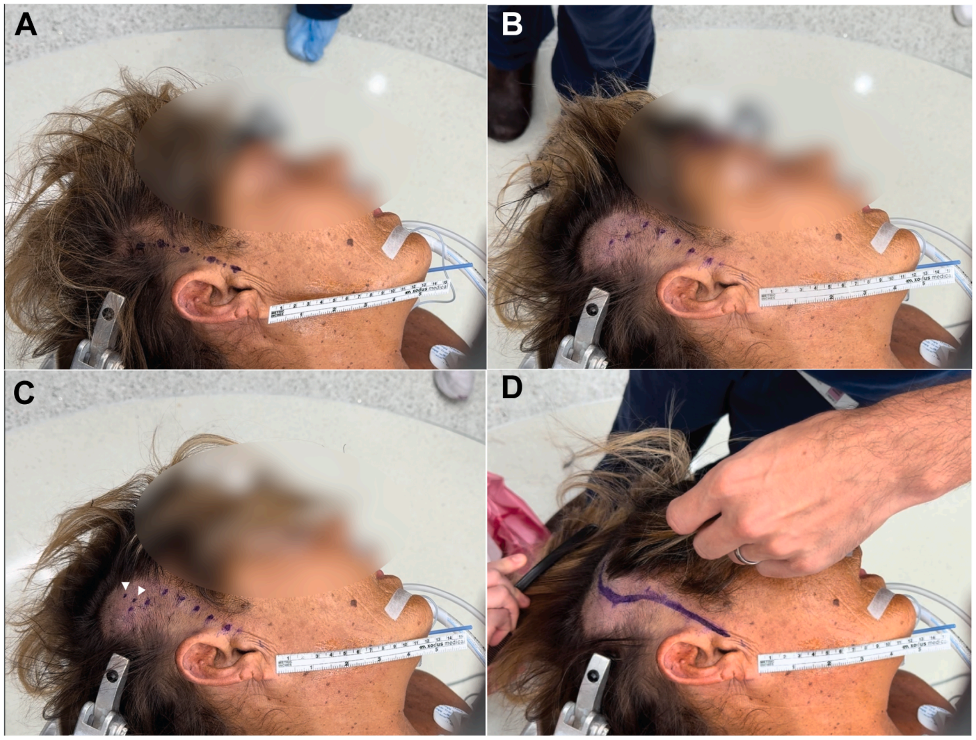

Figure 5. Illustrative case of Patient 006 demonstrating the utility of MR in identifying distal branches of the STA after Doppler mapping. (**A**) MR-guided map. (**B**) Doppler-guided map. (**C**) Doppler-guided map showing the STA with 2 additional distal points identified using MR, indicated by the white arrowheads. These points, located in the distal arm of the STA, were not detected by Doppler mapping alone, highlighting the superiority of MR in identifying distal STA branches. (**D**) Final incision using the mapped points from the combination of Doppler with the additional MR-guided points. MR, mixed reality; STA, superficial temporal artery.

mapping was unable to be conducted. However, as regulatory approval extends into intraoperative use, we anticipate broader applications of MR in cranial neurosurgery.

Finally, while we observed a significant time advantage with isolated MR vessel mapping, this may be offset by the additional time required for MR registration. When incorporating registration time into the analysis, we found that mapping times for MR and Doppler guidance were similar. This was likely due to current limitations in the registration workflow.

Optimizing MR workflow is essential to fully realize its utility in the operative setting and to enable its seamless integration into surgical procedures. Across all 7 cases, patient positioning and optimal placement of the rigid reference array on the forehead ensured consistent visualization and minimized operator adjustments. MR registration relies on simultaneous localization and mapping, a CV technique that is used to provide an intuitive tracking solution for virtual objects. Without a form of ground truth for the MR system during registration, MR images tend to drift.[17,18] Therefore, continuous visualization of the reference array throughout the procedure is essential for precise localization. The tradeoff for maintaining continuous precision and accuracy during registration with a reference array is that it must remain within the headset's field of view. This restricts the surgeon's movements, particularly during the initial registration process. As MR systems evolve, we expect there to be flexible reference arrays or multiarray setups that facilitate rapid registration with greater freedom for the user, thus further improving the operating room workflow.

Future Directions

This proof-of-concept study evaluates the role of MR-guided STA mapping for STA-MCA bypass surgery. While the STA is a commonly mapped and easily identifiable vessel using conventional Doppler techniques, these findings highlight the potential for expanding MR-guided vessel mapping to more complex bypass surgeries. Future applications may include mapping other deep-seated extracranial arteries where Doppler is less effective, such as the occipital artery,[19] as well as tailoring incisions and craniotomies for challenging EC-IC bypass procedures.[6,20] Furthermore, MR guidance may play a role in planning more intricate IC-IC bypasses, mainly through tailoring the craniotomy to allow for unhindered access to donor-recipient vessels.

To further integrate MR into the bypass surgery workflow, real-time overlays that can incorporate hemodynamic and neurophysiology data will be particularly valuable. Additionally, incorporating other imaging adjuncts such as intraoperative microscopic, Doppler, and ICG videoangiography feeds into the MR environment may make intraoperative decision-making more intuitive and streamlined. Moreover, early work has shown that surgeons can perform fine motor tasks using MR displays, underscoring the feasibility of direct surgical interaction within these environments.[21] Taken together, integrating these existing technologies in the operating room may allow MR to become an important dynamic and functional tool in the neurosurgeon's armamentarium. This study represents an important step in validating the use of MR in the operating room, as its utility continues to expand across different operative settings and increasingly complex cerebrovascular procedures.[20,22-25]

Limitations

The sample size of this study was small, and the results should be viewed in that context. Although comparison of MR mapping with true in-situ anatomical location would have allowed us to delineate the precision of the MR mapping method, the precision of the overall system has been previously defined,[26] and our goal was to evaluate the utility of implementing MR as part of a standard OR workflow. Furthermore, MR-based vessel mapping relies on preoperative imaging and may not account for intraoperative vascular changes, such as compression, spasm, or distortion caused by surgical manipulation. Limitations include the potential variability in MR registration accuracy, which can be influenced by patient movement, reference array positioning, and inherent system drift. While efforts were made to standardize registration and workflow across all cases, subtle variations in alignment may have impacted results. Further investigation in a larger cohort is necessary to generalize these findings and optimize MR integration into surgical workflows.

CONCLUSION

This early prospective proof-of-concept study evaluates the role of MR compared to standard Doppler techniques for STA mapping in STA-MCA bypass procedures. We demonstrate that MR achieves comparable alignment and spatial congruence to traditional Doppler mapping while reducing mapping time, suggesting that the incision based on either map is unlikely to change. This study demonstrates the utility of MR to optimize the workflow of STA-MCA bypass surgery and provides an opportunity to shift aspects of current surgical practices into the preoperative phase, expand its application into complex cerebrovascular bypass procedures, and tailor incisions and craniotomies through precise vessel mapping.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Shovan Bhatia: Writing — review & editing, Writing — original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aaron Huynh:** Writing — review & editing, Writing — original draft, Software, Formal analysis, Data curation. **Regan M. Shanahan:** Writing — review & editing, Writing — original draft, Methodology, Investigation, Data curation. **Michael R. Kann:** Writing — review & editing, Visualization, Methodology, Investigation, Data curation. **Adway Gopakumar:** Writing — review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Nikhil Sharma:** Writing — review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Nicolás M. Kass:** Writing — review & editing, Visualization, Supervision, Methodology, Conceptualization. **Griffin Hurt:** Writing — review & editing, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Rishi Basdeo:** Writing — review & editing, Visualization, Software, Methodology, Formal analysis. **Nicole Don:** Writing — review & editing, Writing — original draft, Visualization, Formal analysis. **Michael J. Lang:** Writing — review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Jacob T. Biehl:** Writing — review & editing, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Conceptualization. **Edward G. Andrews:** Writing — review & editing, Visualization, Supervision, Software, Resources, Project administration, Methodology, Investigation, Conceptualization.

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Conflict of interest statement: This material is based on work supported by the National Science Foundation Graduate Research Fellowship under grant numbers DGE2140739 (R. B.) and 2139321 (G.H.).

Parts of this manuscript were presented as an Oral Presentation at the 2024 Congress of Neurological Surgeons (CNS) Annual Meeting in Houston, Texas on October 1, 2024 and as an Oral Presentation at the 2024 Pennsylvania Neurosurgical Society (PNS) Annual Meeting in Hershey, Pennsylvania on July 20, 2024.

Received 14 July 2025; accepted 7 October 2025

Citation: World Neurosurg. (2025) 204:124562.
https://doi.org/10.1016/j.wneu.2025.124562

Journal homepage: **www.journals.elsevier.com/world-neurosurgery**

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