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Combined Use of X-ray Angiography and Intraprocedural MRI Enables Tissue-based Decision Making Regarding Revascularization during Acute Ischemic Stroke Intervention

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Conflicts of interest are listed at the end of this article.

See also the editorial by Lev and Leslie-Mazwi in this issue.

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Background: For patients with acute ischemic stroke undergoing endovascular mechanical thrombectomy with x-ray angiography, the use of adjuncts to maintain vessel patency, such as stents or antiplatelet medications, can increase risk of periprocedural complications. Criteria for using these adjuncts are not well defined.

Purpose: To evaluate use of MRI to guide critical decision making by using a combined biplane x-ray neuroangiography 3.0-T MRI suite during acute ischemic stroke intervention.

Materials and Methods: This retrospective observational study evaluated consecutive patients undergoing endovascular intervention for acute ischemic stroke between July 2019 and May 2020 who underwent either angiography with MRI or angiography alone. Cerebral tissue viability was assessed by using MRI as the reference standard. For statistical analysis, Fisher exact test and Student t test were used to compare groups.

Results: Of 47 patients undergoing acute stroke intervention, 12 patients (median age, 69 years; interquartile range, 60–77 years; nine men) underwent x-ray angiography with MRI whereas the remaining 35 patients (median age, 80 years; interquartile range, 68–86 years; 22 men) underwent angiography alone. MRI results influenced clinical decision making in one of three ways: whether or not to perform initial or additional mechanical thrombectomy, whether or not to place an intracranial stent, and administration of antithrombotic or blood pressure medications. In this initial experience, decision making during endovascular acute stroke intervention in the combined angiography-MRI suite was better informed at MRI, such that therapy was guided in real time by the viability of the at-risk cerebral tissue.

Conclusion: Integrating intraprocedural 3.0-T MRI into acute ischemic stroke treatment was feasible and guided decisions of whether or not to continue thrombectomy, to place stents, or to administer antithrombotic medication or provide blood pressure medications.

Online supplemental material is available for this article.

When successful, endovascular mechanical thrombectomy for acute ischemic stroke reduces death and disability (1). A satisfactory result is inferred from the angiogram at the conclusion of the procedure, on which patency of the target vessel is graded (2). Scenarios arise in which the value of recanalizing a persistently occluded or stenotic large vessel is unclear. Chief among these are situations in which the extent of an evolving cerebral infarct is uncertain and reperfusion may increase the risk of hemorrhage rather than salvage ischemic tissue. Ischemic strokes evolve at different rates (3); reliance on preprocedural imaging alone can result in suboptimal decision making. Discriminating viable tissue from tissue infarct at x-ray angiography is difficult, yet angiography remains the standard modality to determine the end point of the treatment procedure. Diffusion-weighted MRI is the radiologic reference standard to assess cerebral tissue viability. Whereas CT perfusion helps to evaluate kinetics of the passage of iodinated contrast material through cerebral tissue to infer viability, MRI helps to directly assess changes in water diffusivity in cerebral tissue because of cytotoxic edema. Therefore, MRI could play an important role in determining the value of continued attempts to recanalize steno-occlusive lesions or guide future neuroprotective agent use. For instance, placement of an intracranial stent during acute ischemic stroke introduces additional risks including those associated with antiplatelet medications or vessel perforation but may be warranted when viable tissue persists beyond the stenosis.

Abbreviations

DWI = diffusion-weighted imaging, MCA = middle cerebral artery

Summary

In a combined angiography and MRI suite, the management plan for patients with acute ischemic stroke was influenced by intraprocedural MRI in all patients who underwent it.

Key Results

- For endovascular surgery in a combined biplane x-ray neuroangiography 3.0-T MRI suite, neurointerventionalists used MRI in 12 of 47 patients with acute ischemic stroke to determine whether to proceed with mechanical thrombectomy, to place intracranial stents, or to administer antithrombotic or blood pressure medications.
- MRI results influenced the surgical or medical treatment plan for all 12 patients, demonstrating feasibility of the combined use of angiography and MRI.

We present our initial feasibility experience to evaluate the use of MRI to help guide critical decision making by using a combined biplane x-ray neuroangiography 3.0-T MRI suite during acute ischemic stroke intervention.

Materials and Methods

Patients

We retrospectively reviewed all consecutive patients with acute ischemic stroke from large vessel occlusion who underwent emergent neuroendovascular intervention at Zuckerberg San Francisco General Hospital, an affiliate of the University of California San Francisco, between July 2019 and May 2020. Our study was Health Insurance Portability and Accountability Act compliant and institutional review board approved, and written consent was waived. Patients underwent either combined biplane x-ray neuroangiography 3.0-T MRI or intervention guided at angiography alone without intraprocedural MRI in the same interventional suite.

Angiography MRI Suite

Neurovascular intervention at the study hospital is performed with a two-room hybrid solution equipped with a full-featured Artis Q biplane angiographic system (Siemens Healthineers) connected to a full diagnostic Magnetom Skyra 3.0-T MRI (Siemens Healthineers). Patient transport between the two modalities was enabled by a dockable transfer table. The room design also allows for independent use of the two systems. The decision to obtain MRI during neurologic intervention was at the discretion of the attending neurointerventionist. Additionally, the MRI portion of the suite needed to be available (eg, no other patient with an emergent indication for MRI was imaged simultaneously and an MRI technologist was present). The MRI sequences performed were at the discretion of the attending interventional neuroradiologist (see Appendix E1 [online] for sequence parameters).

Clinical and Procedural Data

Patient age, National Institutes of Health Stroke Scale, intubation status, and impact of MRI on decision making were collected from the medical record unblinded and retrospectively. Alberta Stroke Program Early CT Score, MRI findings, MRI sequences performed, MRI coils used, and image acquisition times were collected from picture archiving and communication systems unblinded and retrospectively. Intermodality transfer time was calculated by subtracting the time of the first image of the second modality from the time of the last image of the first modality and included the time for vascular catheter removal and MRI safety screening. For example, for a patient undergoing angiography and then MRI, the intermodality transfer time was the time of the first MRI image subtracted from the time of the last angiography image.

Data Analysis

Medical records and imaging studies were reviewed (K.H.N., with 2 years of experience in interventional radiology, B.F.K., K.M., and J.M.) and interventions were performed (K.H.N., D.M., A.C., C.F.D., V.V.H., R.T.H., D.L.C., and S.W.H., with 15 years of experience in interventional neuroradiology). The utility of MRI findings in clinical decision making, blinded to patient outcomes, was determined and differences in interpretation were resolved by consensus conference (K.H.N., C.H.S., with 2 years of experience in stroke neurology, and S.W.H.). Authors who were not employees or consultants for Siemens had control of all data, including any information that may present a conflict of interest for Siemens.

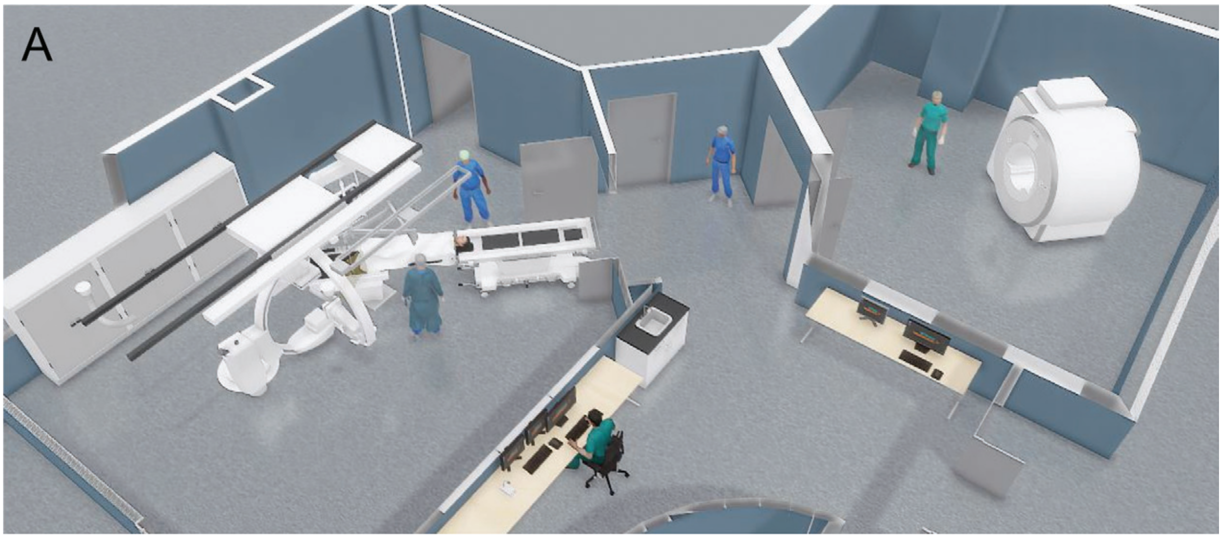
Statistical Analysis

Demographic data were compared between groups by using a Student *t* test for continuous variables (age, National Institutes of Health Stroke Scale score, Alberta Stroke Program Early CT Score, and time of onset to reperfusion) and Fisher exact test for categorical variables (sex, intubation status, occlusion site, modified thrombolysis in cerebral infarction score ≥ 2b) by using software (GraphPad Prism 5.0a; GraphPad). *P* values less than .05 were considered to indicate statistical significance.

Results

Patient Characteristics

Of 47 consecutive patients who underwent intervention for acute stroke, 12 patients (median age, 69 years; interquartile range, 60–77 years; nine men) underwent x-ray angiography with MRI, whereas the remaining 35 patients (median age, 80 years; interquartile range, 68–86 years; 22 men) underwent angiography alone (Fig 1). Age (*P* = .11, Student *t* test), sex (*P* = .50, Fisher exact test), and other clinical characteristics of the 12 patients who underwent MRI during endovascular stroke intervention did not differ from the 35 patients who underwent intervention with angiography alone during the same period (Table 1). In all 12 patients, MRI influenced clinical decision making in three categories: to proceed with



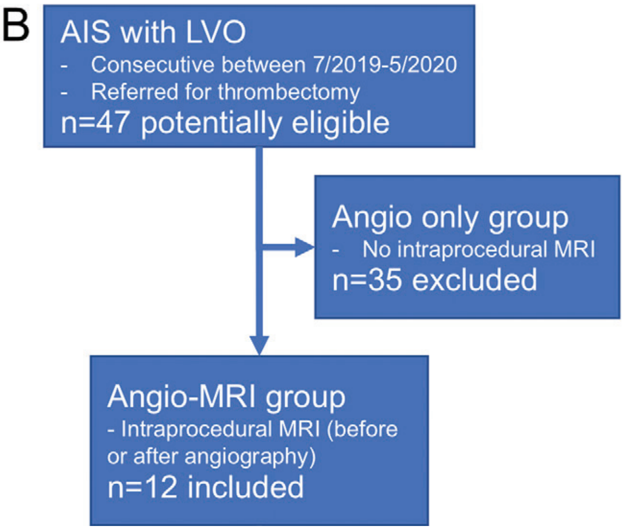


Figure 1: Combined angiography and MRI suite and patient flowchart. *A,* Virtual layout of two-room solution equipped with an Artis Q Biplane angiographic system (left) and a Magnetom Skyra (Siemens Healthineers) 3.0-T MRI system (right), sharing a common control room. Flexible and safe patient transport is enabled by a combi dockable table transfer system. *B,* Flowchart of the patient selection criteria. Forty-seven consecutive patients underwent acute stroke intervention in this suite, of whom 12 patients underwent x-ray angiography with MRI whereas the remaining 35 underwent angiography alone. AIS = acute ischemic stroke, Angio = angiography, LVO = large vessel occlusion.

mechanical thrombectomy, to place intracranial stents, or to administer antithrombotic or pressor medications (Table 2).

MRI-guided Decision to Proceed with Mechanical Thrombectomy

In four patients, MRI helped to guide the decision to proceed with initial or additional thrombectomy. In patients 1 and 2, further mechanical thrombectomy was aborted after initial mechanical thrombectomy resulted in incomplete reperfusion, and MRI depicted acute infarct (Fig 2, Fig E1[online]). In patients 3 and 4, mechanical thrombectomy was pursued after MRI confirmed salvageable tissue without infarct distal to the persistent arterial occlusion, once in a case of acute infarct in territory adjacent to a larger chronic infarct (Fig E2 [online]) and also in a case of M3 middle cerebral artery (MCA) occlusion causing disabling symptoms (Appendix E1 [online]).

MRI-guided Decision to Place Intracranial Stent

In three patients, MRI assisted in deciding whether to place an intracranial stent to treat acutely symptomatic intracranial atherosclerotic disease. Patient 5 (Fig 3) had a right M1 MCA occlusion that manifested more than 3 hours after onset of left hemiparesis. Mechanical thrombectomy of the MCA showed a severe underlying M1 MCA stenosis. Because antiplatelet medications would be needed and increase hemorrhage risk if a stent were placed to keep the M1 MCA patent, the patient was moved to the MRI unit where diffusion-weighted imaging (DWI) showed an infarct in the entire penumbra. Therefore, no stent was placed because reperfusion would have been futile and would have increased the risk for reperfusion hemorrhage. Patient 6 (Fig E3 [online]) presented with more than 24 hours of blood-pressure-dependent left pronator drift. Small posterior cerebral artery–MCA border zone infarcts were shown on DWI scans, and MR angiography helped to identify a critical stenosis of the right cervical petrous internal carotid artery. Because of the small size of the infarcts, the patient was administered antiplatelet medications and a stent was placed in the internal carotid artery stenosis. Patient 7 (Fig E4 [online]) had a right M1 MCA occlusion and left hemiparesis 18 hours after last seen well. CT, CT angiography, and CT perfusion helped to identify a 4-mL core infarction and 114-mL penumbra. DWI helped to differentiate several small acute infarctions from an old right parietal lobe infarction. The patient underwent angiography, and mechanical thrombectomy was performed, which showed an underlying high-grade right M1

Table 1: Demographics of Patients Referred for Acute Stroke Intervention in the Study Period

Parameter	Angiography with MRI (n = 12)	Angiography Only (n = 35)	*P* Value
Median age (y)*	69 (60–77)	80 (68–86)	.11[†]
Sex			.50[‡]
No. of men	9	22	…
No. of women	3	13	…
Median National Institutes of Health Stroke Scale*	16 (11–20)	20 (12–21.5)	.45[†]
Median ASPECTS*	8 (6.5–9)	8 (8–10)	.15[‡]
Intubation	6/12 (50)	13/35 (37)	.51[‡]
Intravenous tPA	4/12 (33)	18/35 (51)	.33[‡]
Occlusion site			.36[‡]
ICA	2/12 (17)	10/35 (29)	…
M1 MCA	6/12 (50)	11/35 (31)	…
M2 MCA	3/12 (25)	12/25 (34)	…
M3/M4 MCA	1/12 (8)	2/35 (6)	…
Basilar artery	1/12 (8)	0/35 (0)	…
mTICI $\geq$ 2b	8/12 (67)	25/35 (71)	>.99[‡]
Median onset to reperfusion (h)*	5:15 (3:40–14:57)	4:56 (3:16–12:19)	.63[†]

Note.—Demographics of 47 patients. Unless otherwise indicated, data are numerator/denominator and data in parentheses are percentages. Median (interquartile range) or n/total (%). ASPECTS = Alberta Stroke Program Early CT Score, ICA = internal carotid artery, MCA = middle cerebral artery, mTICI = modified thrombolysis in cerebral infarction, tPA = tissue plasminogen activator.

* Data in parentheses are interquartile range.

[†] Student *t* test.

[‡] Fisher exact test.

MCA stenosis. The patient was administered a loading dose of antiplatelet therapy, and the MCA underwent angioplasty and a stent was administered (Appendix E1 [online]).

MRI for Antithrombotic Medication Administration and Blood Pressure Goals

MRI helped to guide the use of antithrombotics and helped to dictate blood pressure goals in five additional patients. In patients 8, 9, and 10, MRI helped to inform the use of antithrombotics in the neurocritical care unit on the basis of the extent of cerebral infarct or hemorrhage (Appendix E1 [online]). In patients 11 and 12, MRI helped to determine infarct size and thereby allowed permissive hypertension (Appendix E1 [online]).

MRI Acquisition and Modality Transfer Times

MRI acquisition averaged 12 minutes. One of the following two DWI sequences were performed in all patients who underwent MRI: *(a)* single-shot DWI (by using single-shot echo-planar imaging) and *(b)* readout segmentation of long variable echo-trains DWI (by using readout-segmented echo-planar imaging). For comparable spatial resolution, images from readout segmentation of long variable echo-trains DWI take longer to acquire but have reduced geometric distortion. T2-weighted fluid-attenuated inversion recovery, T2-weighted, T1-weighted, susceptibility-weighted, and time-of-flight MRI angiography sequences were performed in nine of 12 (75%), six of 12 (50%), five of 12 (42%), three of 12 (25%), and two of 12 (17%) patients, respectively. MRI scans were acquired by using either two flexible multichannel receive coils (18-channel anterior with four-channel posterior) or a rigid 20-channel head-neck coil. Time to transfer a patient between modalities averaged 45 minutes (Table 1).

Discussion

For patients with acute ischemic stroke who undergo mechanical thrombectomy, use of adjuncts to maintain vessel patency can increase risk of periprocedural complications. Criteria for the use of these adjuncts are not well defined. Our study showed that combined use of angiography and MRI during endovascular stroke intervention enabled tissue-based decision making to determine whether or not to proceed with mechanical thrombectomy, place intracranial stents, or administer antithrombotic or blood pressure medications. MRI influenced the surgical or medical treatment plan for all patients, which demonstrated the use of the combined use of angiography and MRI.

Although clinical trials have shown the effectiveness of mechanical thrombectomy (4–7), stopping points for interventions that do not achieve complete or near-complete reperfusion are poorly defined (8). Trials have also raised safety concerns regarding endovascular treatment of intracranial atherosclerotic disease. The periprocedural complication rate in the endovascular treatment arm of the Stenting and Aggressive Medical Management for Preventing Recurrent Stroke in Intracranial Stenosis, or SAMMPRIS, trial was 15% (9), whereas the Wingspan Stent System Postmarket Surveillance, or WEAVE, registry reported an adverse effect rate of 2.6% in carefully selected patients (10). Whereas some retrospective studies suggested that administering rescue intracranial stents is safe and effective after failed mechanical thrombectomy, rates of intracranial hemorrhage and death are high (11–13). Multimodality imaging suites may provide added value in these challenging cases (14) because optimal delineation of the location and volume of tissue infarct is essential for decision making during stroke treatment.

Table 2: Summary of Patients Who Underwent MRI during Acute Stroke Intervention

										MRI Sequences Performed	
Significance of MRI	Age (y)	NIHSS Score	ASPECTS	Intubation	MRI Findings	Impact of MRI Interpretation on Decision Making	Workflow	Intermodality Transfer Time (min)[*]	MRI Acquisition Time (min)[†]	Before Intervention	After Intervention
Whether or not to proceed with mechanical thrombectomy											
Patient No. 1	48	17	7	Yes	Large MCA infarct	No further MT	Angiography to MRI	28	1		RESOLVE DWI
Patient No. 2	57	30	8‡	Yes	Large acute infarct	No further MT	Angiography to MRI	30	14		RESOLVE DWI, SS DWI, T2w FLAIR 2D, SWI, T1w 2D
Patient No. 3	59	17	4	No	Acute infarct spares left primary motor cortex; left temporal/insular infarct is chronic	Continue with MT	MRI to angiography to MRI	25[§], 40[‖]	17[#], 12[**]	RESOLVE DWI, SS DWI, T2w FLAIR 2D, T1w 2D	RESOLVE DWI, SS DWI, T2w 2D, TOF MRI angiography, SWI
Patient No. 4	74	11	10	No	Small acute infarct	Continue with MT	Angiography to MRI to angiography	45[‖], 46[§]	7	RESOLVE DWI, T2w FLAIR 2D	RESOLVE DWI, SS DWI, T2w FLAIR 2D, T1w 2D, T2w 2D
Whether or not to proceed with stent placement											
Patient No. 5	75	20	6	No	Large acute infarct	Do not place intracranial stent	Angiography to MRI	28	8		RESOLVE DWI, SS DWI

Table 2 *(continues)*

Table 2 *(continued)*: Summary of Patients Who Underwent MRI during Acute Stroke Intervention

Significance of MRI	Age (y)	NIHSS Score	ASPECTS	Intubation	MRI Findings	Impact of MRI Interpretation on Decision Making	Workflow	Intermodality Transfer Time (min)*	MRI Acquisition Time (min)†	MRI Sequences Performed	
										Before Intervention	After Intervention
Patient No. 6	83	1	9	Yes	Borderzone infarcts due to watershed ischemia	Place intracranial stent	MRI to angiography	45	47	RESOLVE DWI, T2w FLAIR 2D, SWI, T1w 3D, T2w 2D, T1w 2D, TOF MR angiography	
Patient No. 7	64	10	7	Yes	Small acute infarct	Place intracranial stent	MRI to angiography	59	10	RESOLVE DWI, SS DWI, T2w FLAIR 2D, T1w 2D, T2w 2D	
Critical care management											
Patient No. 8	60	15	10	No	Medium acute infarct; small petechial hemorrhage	PE treatment with tPA if indicated	Angiography to MRI	25	8		RESOLVE DWI, SWI, T2w FLAIR 2D
Patient No. 9	68	12	8	No	Small acute infarct	Continue IV heparin; permissive hypertension	Angiography to MRI	21	8		RESOLVE DWI, T2w FLAIR 2D, T2w 2D
Patient No. 10	101	20	6	No	Medium acute infarct	Warfarin anticoagulation in 2 weeks	Angiography to MRI	35	12		RESOLVE DWI, SS DWI, T2w FLAIR 2D
Patient No. 11	86	23	9	Yes	Medium acute infarct	Permissive hypertension	Angiography to MRI	121	6		RESOLVE DWI, SS DWI
Patient No. 12	69	11	9	Yes	Small acute infarct	Permissive hypertension	Angiography to MRI	77	8		RESOLVE DWI, SS DWI, T2w FLAIR 2D, T2w 2D

Note.—Summary is of 12 patients. ASPECTS = Alberta Stroke Program Early CT Score, DWI = diffusion-weighted imaging, FLAIR = fluid-attenuated inversion recovery, IV = intravenous, MCA = middle cerebral artery, MT = mechanical thrombectomy, NIHSS = National Institutes of Health Stroke Scale, PE = pulmonary embolism, RESOLVE = readout segmentation of long variable echo trains, SS = single shot, SWI = susceptibility-weighted imaging, SD = standard deviation, TOF = time of flight, tPA = tissue plasminogen activator, T1w = T1 weighted, T2w = T2 weighted, 3D = three-dimensional, 2D = two-dimensional.

*Average time, 45 minutes ± 27 (standard deviation).

† Average time, 12 minutes ± 11.

‡ Posterior circulation Alberta Stroke Program Early CT Score.

§ MRI to angiography.

‖ Angiography to MRI.

Before intervention.

** After intervention.

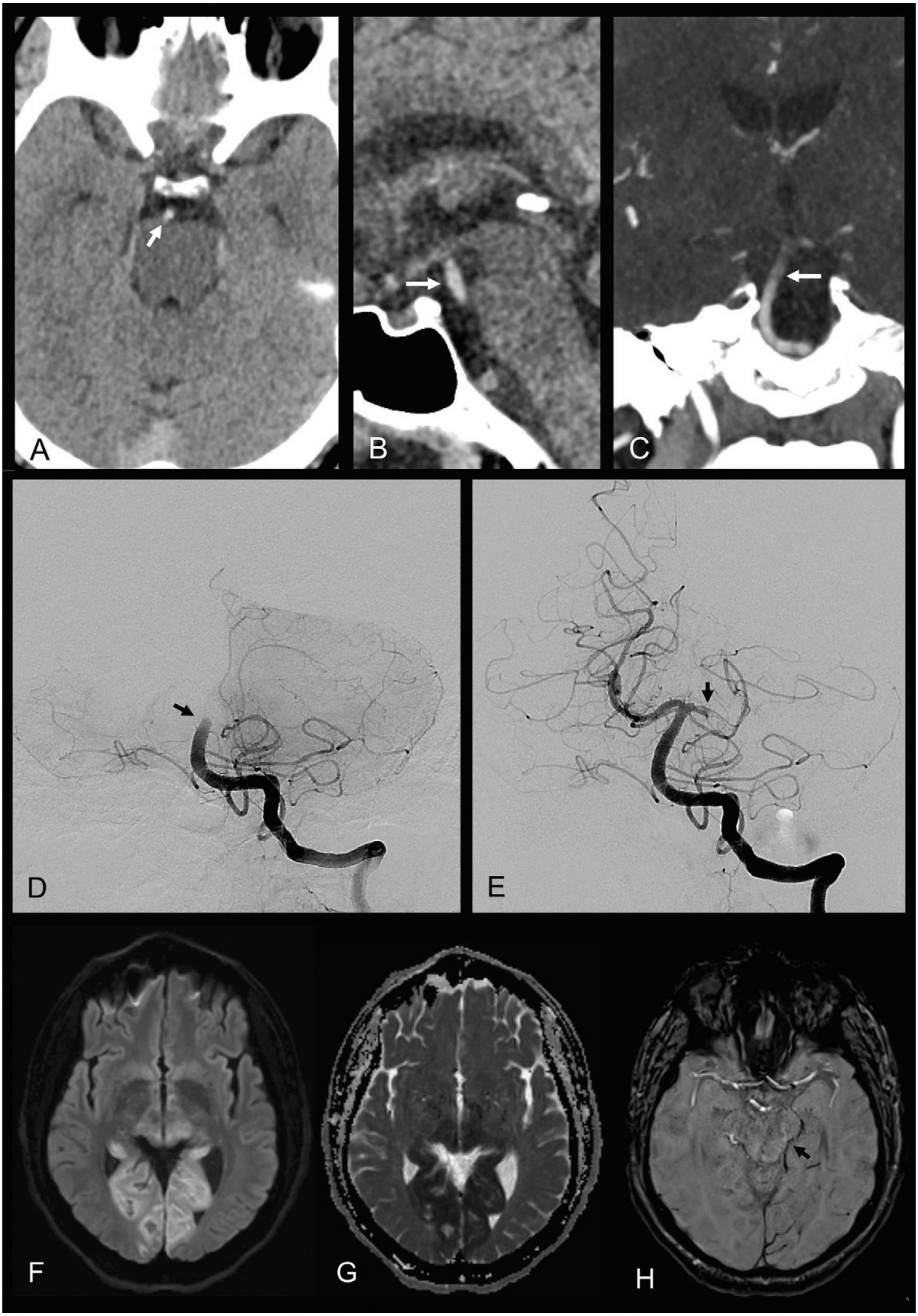


Figure 2: Mechanical thrombectomy in a 57-year-old man with recanalization of the basilar artery but the left posterior cerebral artery remains occluded. *A,* Axial and, *B,* sagittal noncontrast head CT images show hyperattenuated thrombus (arrow) in the distal basilar artery. *C,* Coronal CT angiography shows nonopacity of the distal basilar artery (arrow). Left vertebral arteriogram in frontal projection, *D,* before and, *E,* after mechanical thrombectomy demonstrate recanalization of the basilar artery but occlusion of the left posterior cerebral artery (arrows). *F,* Axial diffusion-weighted imaging and, *G,* apparent diffusion coefficient map show acute infarct in the bilateral posterior cerebral artery territories with increased susceptibility in the left posterior cerebral artery (arrow on *H*) and, *H,* axial susceptibility-weighted imaging, mitigating against further mechanical thrombectomy attempts.

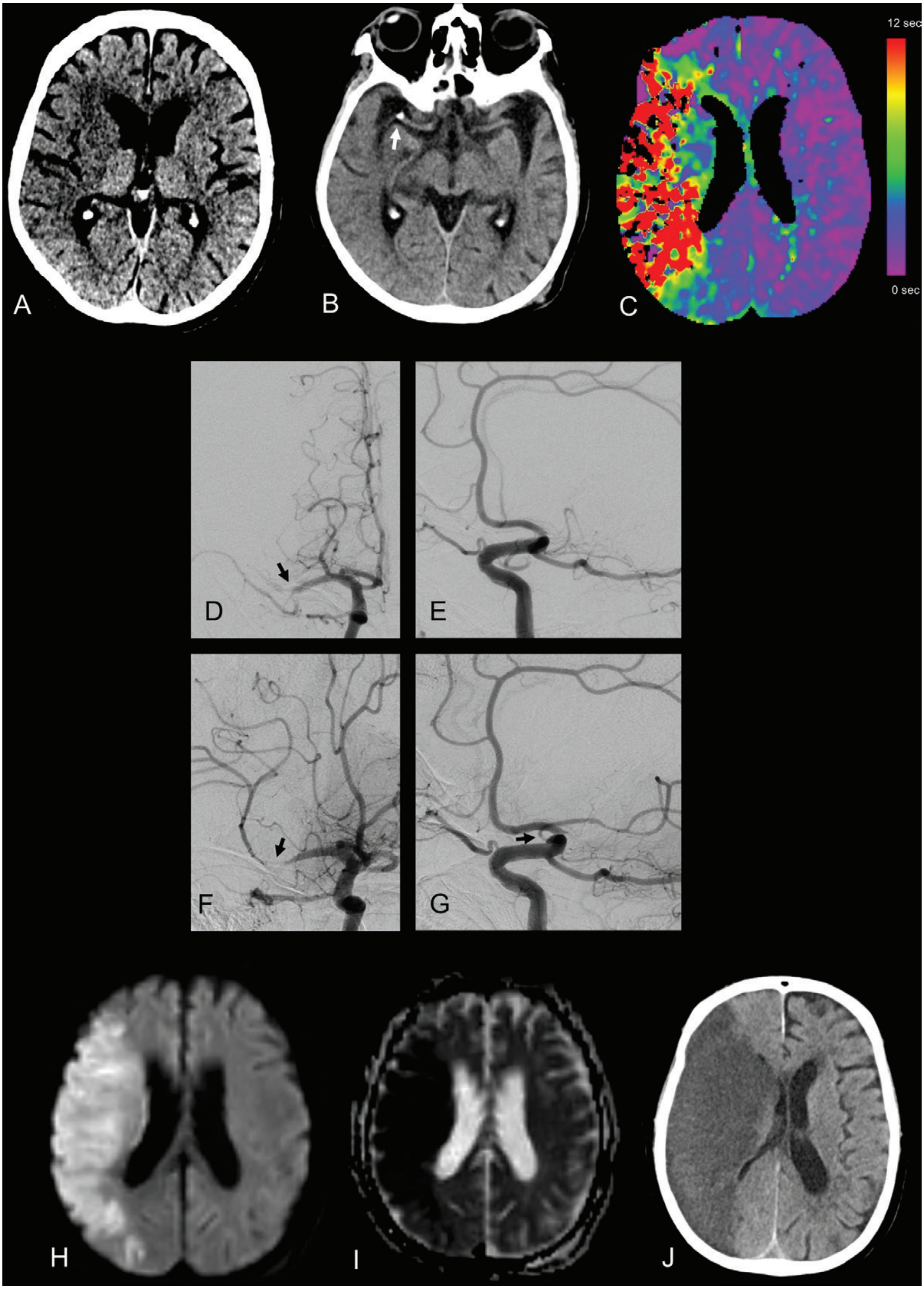


Figure 3: Mechanical thrombectomy in a 75-year-old man shows underlying intracranial atherosclerotic disease. *A,* Noncontrast head CT image on the axial plane shows multiple areas of subtle hypoattenuation in the right middle cerebral artery (MCA) distribution (Alberta Stroke Program Early CT Score, 6). *B,* Noncontrast head CT image on the axial plane shows calcified lesion in the right M1 middle cerebral artery (arrow). *C,* Time to maximum of residue function map on the axial plane shows large area of tissue at risk in the right MCA territory. Right common carotid arteriograms of, *D,* frontal and, *E,* lateral projections before attempted thrombectomy show occlusion of the distal M1 segment of the right MCA (arrow; thrombolysis in cerebral infarction score of 0). Right internal carotid arteriograms of, *F,* frontal and, *G,* lateral projections after three thrombectomy passes show antegrade flow through a high-grade stenosis (arrow) in the right distal M1 MCA, *(Fig 3 continues).*

Although CT perfusion is widely available, core infarct estimation is imprecise and may be inaccurate depending on software parameters used (15) or whether iodinated contrast agent was recently administered (16). Consensus has not been reached regarding the best parameter (eg, cerebral blood volume, cerebral blood flow, and regional cerebral blood flow), threshold values, or algorithms for core infarct definition. MRI accurately depicts core infarct with a superior contrast-to-noise ratio (17,18). In our experience, MRI incorporated into the neuroangiography suite depicts the extent of tissue infarct, which can evolve rapidly.

Although the MRI environment poses tooling constraints, interventional MRI has already been used in other settings and is ready to have a role in endovascular treatment (19). Our institution has a two-room setup with a biplane neuroangiography unit and 3.0-T MRI used for neurologic intervention that allows for independent use of the two systems. Other institutions have biplane angiography units and 1.5.0-T MRI systems from Siemens (20) or Philips (21) for interventional cardiology, or a three-room solution with single-plane angiography, wide-bore 3.0-T MRI, and PET/CT (22). Moveable MRI systems have been deployed at multiple sites (23) (24), necessitating development of MRI-compatible equipment. Our study used standard clinical radiography-compatible catheters that were removed before patient transfer to MRI, leaving only short plastic vascular access sheaths in the femoral arteries of the patients. Development of MRI-compatible catheters could facilitate MRI use during radiography-guided endovascular procedures (25–28) because these devices could remain in place at intraoperative MRI, thus streamlining combined x-ray neuroangiography 3.0-T MRI workflows, maximizing patient safety, and eventually enabling real-time navigation not only at radiography but also at MRI.

Our study had limitations. This was a nonrandomized, retrospective, single-center study of 12 patients who underwent x-ray angiography with MRI; therefore, our study was prone to confounding or selection bias. Historical control data are limited (Table 1). The additional time needed to undergo intraprocedural MRI may have caused further infarct progression that offset benefits achieved with knowledge of MRI results.

To conclude, our study showed that combined use of angiography and MRI during endovascular acute ischemic stroke intervention is feasible and enabled tissue-based decision making regarding whether or not to proceed with mechanical thrombectomy, place intracranial stents, or administer antithrombotic or blood pressure medications. Further development of combined biplane x-ray neuroangiography 3.0-T MRI and related devices would enable cerebrovascular intervention on the basis of real-time assessment of tissue viability rather than inference of tissue state on the basis of time or preprocedure imaging alone.

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Figure 3 *(continued)***:** with antegrade flow into the posterior M2 division but persistent occlusion of the anterior M2 division of the right MCA. *H,* Axial diffusion-weighted image and, *I,* apparent diffusion coefficient map demonstrate a large region of reduced diffusion in the right MCA territory (apparent diffusion coefficient, 403 × 10^{-6} mm^2/sec), compatible with cytotoxic edema from acute infarct, warranting no stent placement. *J,* Follow-up noncontrast head CT images on the axial plane obtained 2 days after MRI shows extent of right MCA territory infarct.

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