RESEARCH PAPER

A Cross-Sectional Study to Evaluate the Outcomes of Brain MRI, MR Angiography, and Carotid Doppler Ultrasound in Smoking Versus Non-Smoking Patients with Ischemic Stroke: A Review on Multimodal Imaging in Ischemic Stroke and Therapeutic Decision-Making

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Abstract

Ischemic stroke is a leading cause of mortality and long-term disability worldwide, and timely imaging is central to effective management. Magnetic resonance imaging (MRI), magnetic resonance angiography (MRA), and carotid Doppler ultrasound (CDUS) each provide distinct but complementary perspectives on brain and vascular pathology. MRI is highly sensitive for detecting acute ischemic changes, particularly with diffusion-weighted imaging, which can reveal infarcts within minutes of onset. Perfusion sequences further help identify tissue at risk, guiding urgent therapeutic decisions. MRA adds crucial information by delineating intracranial and extracranial vascular anatomy, detecting stenosis, occlusion, or dissection, and supporting decisions about endovascular intervention. CDUS, in contrast, offers a rapid, non-invasive evaluation of extracranial carotid arteries, quantifying stenosis and assessing hemodynamic relevance, which is vital for determining candidacy for carotid endarterectomy or stenting. Together, these modalities shape both immediate and long-term management. MRI lesion volume correlates with functional prognosis, MRA findings inform recurrence risk, and CDUS supports vascular surveillance. Importantly, their integration enhances diagnostic accuracy: MRI defines tissue viability, MRA maps vascular pathology, and CDUS evaluates extracranial flow dynamics. This multimodal approach reduces misdiagnosis, ensures timely intervention, and enables individualized treatment planning. In summary, while each technique has unique strengths, their combined use provides a comprehensive view of ischemic stroke. Multimodal imaging is not simply additive but essential, offering a holistic framework that improves acute care and long-term outcomes.

Key words: Magnetic resonance angiography; Carotid Doppler ultrasound; Magnetic resonance imaging; Ischemic stroke

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Introduction

Stroke is a major cause of global morbidity and mortality, with ischemic stroke representing the majority of cases (1). The pathophysiology involves arterial occlusion that reduces cerebral blood flow, leading to infarction of brain tissue and often resulting in long-term neurological deficits (2). Imaging is indispensable in this context, serving not only to confirm ischemia and exclude hemorrhage but also to characterize the extent of tissue injury, identify salvageable penumbra, and evaluate vascular lesions that may guide intervention (3,4).

Computed tomography (CT) remains the most accessible and rapid first-line modality, particularly for ruling out intracranial hemorrhage before thrombolytic therapy (5). However, advanced techniques such as magnetic resonance imaging (MRI), magnetic resonance angiography (MRA), and carotid Doppler ultrasound (CDUS) provide superior sensitivity and specificity in many scenarios. MRI, especially diffusion-weighted imaging, can detect ischemic changes within minutes of onset, while perfusion imaging helps delineate tissue at risk (6,7). MRA offers detailed visualization of intracranial and extracranial vessels, identifying stenosis, occlusion, or dissection, which is critical for planning endovascular therapy. CDUS provides a rapid, non-invasive assessment of extracranial carotid arteries, quantifying stenosis and evaluating hemodynamic significance, thereby guiding decisions regarding carotid endarterectomy or stenting.

The combined use of these modalities—multimodal imaging—offers a comprehensive assessment that informs both acute

management and secondary prevention strategies. MRI defines tissue viability, MRA maps vascular pathology, and CDUS evaluates extracranial flow dynamics. Together, they enhance diagnostic accuracy, reduce misdiagnosis, and support individualized treatment planning. Prognostically, lesion volume on MRI correlates with functional outcomes, MRA findings predict recurrence risk, and CDUS contributes to long-term vascular surveillance (8).

While CT remains indispensable for rapid triage, MRI, MRA, and CDUS provide deeper insights into parenchymal injury, vascular anatomy, and extracranial hemodynamic. Their integration ensures timely intervention, optimizes therapeutic decision-making, and improves both immediate and long-term outcomes. Multimodal imaging is therefore not simply complementary but essential in modern stroke care (8).

Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging (MRI) is the most sensitive modality for detecting early ischemic changes in acute stroke and has become central to modern neuroimaging practice. Its ability to capture subtle alterations in brain tissue within minutes of symptom onset makes it invaluable for both diagnosis and therapeutic decision-making (9).

Diffusion-weighted imaging (DWI) is the cornerstone sequence, capable of identifying cytotoxic edema almost immediately after arterial occlusion (10). This rapid detection distinguishes viable tissue from irreversibly damaged regions, allowing clinicians to act promptly. Fluid-attenuated inversion recovery (FLAIR) sequences complement DWI by providing temporal information, helping to differentiate acute from chronic lesions. The combination of DWI and FLAIR is particularly useful in determining stroke onset time, which is critical for eligibility in reperfusion therapies.

Perfusion-weighted imaging (PWI) adds further depth by delineating hypoperfused but still viable tissue—the ischemic penumbra (11). Identifying this penumbra is essential, as it represents the therapeutic target for interventions aimed at restoring blood flow and preventing infarction progression. Susceptibility-weighted imaging (SWI) contributes additional value by detecting microbleeds and thrombus susceptibility signs, which can influence both prognosis and treatment selection.

MRI also plays a pivotal role in prognosis. Lesion volume on DWI correlates strongly with functional outcomes, offering predictive value for recovery potential. The DWI/PWI mismatch serves as a biomarker for therapeutic benefit from reperfusion therapies, guiding decisions about thrombolysis and thrombectomy. Importantly, MRI has expanded the therapeutic window for thrombolysis, allowing treatment beyond conventional time limits in carefully selected patients. It also informs thrombectomy eligibility by providing detailed anatomical and tissue viability data (12).

Despite these strengths, MRI has limitations. Restricted availability in many regions, contraindications in patients with metallic implants or severe claustrophobia, and logistical challenges in unstable or critically ill patients can hinder its use. Transporting unstable patients to the MRI suite may pose risks, and longer scan times can be problematic in emergency settings. Cost and accessibility remain barriers in resource-limited environments, where CT often remains the primary imaging modality (11).

Nevertheless, the advantages of MRI in acute ischemic stroke are profound. Its ability to detect early changes, define tissue viability, and guide individualized therapy makes it a cornerstone of advanced stroke imaging. When integrated with other modalities such as CT, magnetic resonance angiography (MRA), and carotid Doppler ultrasound (CDUS), MRI contributes to a multimodal approach that enhances diagnostic accuracy, informs acute management, and supports secondary prevention strategies (13).

MRI offers unparalleled sensitivity and specificity for early ischemic stroke detection. DWI, FLAIR, PWI, and SWI together provide a comprehensive assessment of parenchymal injury, vascular status, and tissue viability. While practical limitations exist, the prognostic and therapeutic insights gained from MRI make it an essential tool in modern stroke care. Its role in extending treatment windows and refining patient selection for reperfusion therapies underscores its transformative impact on outcomes (14).

Magnetic Resonance Angiography (MRA)

Magnetic resonance angiography (MRA) is a cornerstone technique in the evaluation of ischemic stroke, offering non-invasive visualization of both intracranial and extracranial vessels. Unlike conventional angiography, MRA avoids arterial puncture and radiation exposure, making it safer and more accessible for repeated use. Two principal approaches are employed: time-of-flight (TOF) MRA, which does not require contrast agents and is particularly useful in patients with contraindications to gadolinium, and contrast-enhanced MRA, which improves accuracy in detecting stenosis, occlusion, and vascular anomalies (15).

MRA is especially valuable in identifying large vessel occlusions (LVOs), dissections, and intracranial stenosis. These findings are critical in acute stroke management, as LVOs often necessitate mechanical thrombectomy, while dissections and stenoses may require tailored medical or interventional strategies. Beyond diagnosis, MRA provides prognostic information: vessel patency and collateral circulation patterns assessed through MRA strongly predict functional outcomes and risk of recurrence. Patients with robust collateral networks often fare better, even in the presence of significant occlusion, underscoring the importance of vascular imaging in outcome prediction (16).

Therapeutically, MRA is indispensable in selecting candidates for mechanical thrombectomy, guiding stenting or angioplasty in intracranial atherosclerosis, and informing long-term vascular management. It allows clinicians to stratify patients based on vascular anatomy and collateral status, ensuring that interventions are directed toward those most likely to benefit.

Despite its strengths, MRA has limitations. Motion artifacts can degrade image quality, particularly in restless or critically ill patients. Sensitivity for distal branch occlusions is reduced compared to digital subtraction angiography (DSA), which remains the gold standard for fine vascular detail. Additionally, TOF MRA may overestimate stenosis due to flow-related artifacts, while contrast-enhanced techniques carry risks in patients with renal impairment (17).

Nevertheless, MRA remains a cornerstone in vascular imaging for ischemic stroke. Its ability to non-invasively map vascular anatomy, detect critical lesions, and provide prognostic insights makes it integral to both acute and chronic stroke care. When combined with other modalities such as MRI, CT angiography, and carotid Doppler ultrasound, MRA contributes to a multimodal imaging strategy that enhances diagnostic accuracy, guides therapy, and improves patient outcomes.

MRA bridges the gap between diagnosis and intervention in ischemic stroke. By identifying occlusions, assessing collateral circulation, and guiding therapeutic decisions, it plays a pivotal role in modern stroke management. While limitations exist, its non-invasive nature and comprehensive vascular assessment ensure that MRA continues to be a vital tool in both acute and long-term care.

Carotid Doppler Ultrasound (CDUS)

Carotid Doppler ultrasound (CDUS) is the first-line tool for evaluating extracranial carotid artery disease, which is a major contributor to ischemic stroke. Its non-invasive nature, bedside availability, and repeatability make it an indispensable technique in both acute and preventive stroke care. CDUS quantifies stenosis severity using peak systolic velocity and end-diastolic velocity, providing reliable estimates of luminal narrowing. In addition, it characterizes plaque morphology, distinguishing echolucent vulnerable plaques from calcified stable ones. Vulnerable plaques, particularly those with ulceration or intraplaque hemorrhage, are associated with a higher risk of embolization and recurrent stroke (18).

From a prognostic standpoint, CDUS findings are highly significant. High-grade stenosis strongly predicts recurrent stroke risk, and plaque vulnerability features refine risk stratification beyond simple luminal narrowing. Patients with unstable plaques are more likely to experience cerebrovascular events even in the absence of severe stenosis, underscoring the importance of plaque characterization. CDUS thus provides both quantitative and qualitative information that informs clinical decision-making (18).

Therapeutically, CDUS guides interventions such as carotid endarterectomy (CEA) or carotid artery stenting (CAS). Accurate measurement of stenosis severity is critical in determining candidacy for these procedures, particularly in symptomatic patients with moderate to severe stenosis. CDUS also plays a role in long-term surveillance after intervention, monitoring restenosis and evaluating the durability of surgical or endovascular treatment. Its ability to be repeated safely and conveniently makes it ideal for follow-up imaging.

The advantages of CDUS are clear: it is non-invasive, widely available, relatively inexpensive, and can be performed at the bedside, even in critically ill patients. It does not expose patients to radiation or contrast agents, making it suitable for repeated use. However, limitations must be acknowledged. CDUS is operator-dependent, with accuracy influenced by the skill and experience of the sonographer. It also has reduced ability to visualize intracranial vessels, limiting its scope to extracranial carotid arteries. In cases where distal or intracranial pathology is suspected, complementary imaging such as CT angiography or magnetic resonance angiography is required (19).

Despite these limitations, CDUS remains a cornerstone in the evaluation of carotid artery disease. Its role in quantifying stenosis, characterizing plaque vulnerability, predicting prognosis, and guiding therapeutic decisions makes it indispensable in both acute and secondary prevention of ischemic stroke. When integrated into a multimodal imaging strategy alongside MRI, MRA, and CT, CDUS enhances diagnostic accuracy and supports individualized patient care.

CDUS provides critical insights into extracranial carotid pathology, balancing accessibility with diagnostic utility. By combining hemodynamic assessment with plaque characterization, it informs risk stratification and therapeutic planning. While operator dependence and limited intracranial visualization are challenges, its strengths in non-invasiveness, bedside applicability, and repeatability ensure that CDUS continues to play a vital role in modern stroke management.

Comparative Roles and Integration

Magnetic resonance imaging, magnetic resonance angiography, and carotid duplex ultrasonography together form a triad of complementary modalities that have become central to the management of ischemic stroke. Each technique contributes unique strengths, and their integration across the continuum of care allows clinicians to achieve comprehensive diagnosis, individualized prognosis, and evidence-based therapeutic decisions. MRI is unparalleled in its ability to assess brain parenchyma, detecting both the infarct core and the ischemic penumbra with unmatched sensitivity. Diffusion-weighted imaging can reveal cytotoxic edema within minutes of arterial occlusion, while perfusion-weighted imaging highlights

hypoperfused but potentially salvageable tissue. This distinction between irreversibly damaged brain and viable tissue is critical in guiding reperfusion therapies, particularly in extended time windows where eligibility for thrombolysis or thrombectomy must be carefully determined. Beyond acute infarct detection, MRI provides insights into stroke onset timing through FLAIR sequences, evaluates hemorrhagic transformation with susceptibility-weighted imaging, and characterizes small vessel disease and white matter changes that influence long-term prognosis. Its comprehensive parenchymal evaluation makes MRI indispensable in modern stroke care (20).

MRA complements MRI by providing vascular mapping essential for intervention planning. It allows non-invasive visualization of intracranial and extracranial arteries, detecting stenosis, occlusion, or aneurysmal changes. In the acute setting, MRA identifies large vessel occlusions that determine eligibility for mechanical thrombectomy, a therapy that has dramatically improved outcomes in selected patients. It also plays a role in monitoring intracranial stenosis, guiding decisions regarding stenting, angioplasty, or intensified medical therapy. Unlike digital subtraction angiography, MRA avoids radiation and contrast nephrotoxicity, making it safer for repeated follow-up. Techniques such as time-of-flight MRA and contrast-enhanced MRA provide flexibility depending on patient factors and clinical needs. By delineating vascular anatomy, MRA bridges the gap between parenchymal imaging and therapeutic intervention, ensuring that treatment strategies are anatomically precise and tailored to the vascular pathology underlying the ischemic event.

Carotid duplex ultrasonography, in contrast, remains the gold standard for evaluating extracranial carotid disease. Its portability, cost-effectiveness, and non-invasive nature make it ideal for widespread use in both acute and chronic settings. By combining B-mode imaging with Doppler flow analysis, CDUS not only quantifies stenosis severity but also characterizes plaque morphology, identifying features such as ulceration or intraplaque hemorrhage that confer heightened risk. In clinical practice, CDUS is pivotal for intervention planning, as patients with symptomatic high-grade carotid stenosis benefit from carotid endarterectomy or stenting. It also plays a central role in secondary prevention, where serial examinations track disease progression and therapeutic efficacy. Unlike MRI and MRA, CDUS can be performed at the bedside, making it particularly useful in unstable patients or those contraindicated for advanced imaging. Its role in long-term monitoring ensures that patients remain under surveillance for recurrent risk, anchoring the preventive arm of stroke care and ensuring that vascular disease progression is detected early enough to allow timely intervention (21).

The integration of these modalities into clinical workflow reflects a layered approach tailored to different phases of management. In the hyperacute phase, CT remains the initial modality due to its speed and availability, primarily to exclude hemorrhage. However, MRI and MRA are increasingly utilized in extended time windows, refining treatment eligibility by distinguishing viable tissue from infarct core and mapping vascular occlusions. This shift is supported by evidence demonstrating the benefit of advanced imaging-guided reperfusion therapies beyond conventional time limits. CDUS, meanwhile, assumes prominence in the subacute and chronic phases, where the focus shifts to identifying and mitigating risk factors for recurrence. Its ability to monitor carotid disease progression and guide timely intervention makes it indispensable in secondary prevention strategies. The sequential application of these modalities ensures that patients benefit from rapid triage, precise intervention, and long-term surveillance, embodying a continuum of care that addresses both the acute event and its underlying causes.

Together, MRI, MRA, and CDUS form a synergistic triad that addresses the full spectrum of ischemic stroke pathology. MRI defines the parenchymal consequences of vascular occlusion, MRA maps the arterial tree to identify the culprit lesion, and CDUS evaluates extracranial carotid disease that often underlies the event. This triad enables individualized prognosis, guiding therapeutic decisions that range from thrombolysis and thrombectomy to surgical intervention and medical management. The synergy lies not only in their complementary strengths but also in their sequential application across the continuum of care. MRI and MRA dominate the acute and subacute phases, refining diagnosis and intervention strategies, while CDUS anchors long-term prevention. Together, they embody the principle of precision medicine, tailoring care to the unique anatomical and physiological profile of each patient. The evolution of stroke imaging has transformed clinical practice, shifting from reliance on CT alone to a multimodal approach that leverages the complementary strengths of MRI, MRA, and CDUS. MRI provides unparalleled sensitivity in detecting infarct core and penumbra, MRA offers detailed vascular mapping essential for thrombectomy and intracranial stenosis management, and CDUS remains the gold standard for extracranial carotid disease evaluation. Their integration into clinical workflow ensures comprehensive diagnosis, individualized prognosis, and evidence-based therapeutic decisions. As imaging technology continues to advance, this triad will remain central to stroke care, embodying the synergy between parenchymal and vascular assessment, acute intervention and chronic prevention, and diagnostic precision with therapeutic impact. In this way, MRI, MRA, and CDUS together represent not merely diagnostic tools but essential pillars of modern ischemic stroke management, ensuring that

patients receive care that is timely, targeted, and tailored to their individual needs.

Emerging Trends

Emerging trends in ischemic stroke care are increasingly shaped by advances in imaging, therapeutics, and preventive strategies, reflecting a shift toward precision medicine and individualized patient management. One of the most significant developments is the expansion of treatment windows for reperfusion therapies. Traditionally, intravenous thrombolysis was limited to 4.5 hours after symptom onset, and mechanical thrombectomy to 6 hours. However, recent trials using advanced imaging selection criteria have demonstrated benefit in carefully chosen patients up to 16–24 hours after onset. This has redefined the role of MRI and CT perfusion imaging, which now serve as gatekeepers for extended-window interventions, ensuring that patients with salvageable tissue are not excluded from potentially life-saving therapies (22).

Another emerging trend is the refinement of imaging modalities themselves. MRI continues to evolve with faster acquisition protocols, making it more feasible in acute settings. MRA is being enhanced by high-resolution techniques that improve visualization of distal vessels and plaque characterization. CDUS is increasingly incorporating three-dimensional and contrast-enhanced approaches, allowing for more detailed assessment of carotid plaque vulnerability. These innovations are not only improving diagnostic accuracy but also enabling risk stratification, which is critical for secondary prevention. The integration of multimodal imaging into routine practice reflects a broader trend toward comprehensive evaluation, where parenchymal, vascular, and hemodynamic information is synthesized to guide management (11).

Therapeutically, there is growing emphasis on individualized antithrombotic strategies. While dual antiplatelet therapy has shown benefit in certain high-risk populations, ongoing research is exploring novel agents and tailored regimens based on genetic, metabolic, and imaging-derived risk profiles. Endovascular techniques are also advancing, with newer thrombectomy devices designed to improve first-pass success and reduce complications. The role of stenting in intracranial stenosis remains under investigation, but technological improvements are making these interventions safer and more effective. Parallel to these developments, there is increasing recognition of the importance of neuroprotection. Agents targeting excitotoxicity, oxidative stress, and inflammation are being studied as adjuncts to reperfusion, aiming to preserve neuronal integrity and improve functional outcomes.

Preventive strategies are also undergoing transformation. CDUS remains central to carotid disease surveillance, but its role is being expanded through integration with systemic risk assessment tools. Lifestyle modification, aggressive risk factor control, and pharmacological interventions are being tailored to imaging findings, creating a feedback loop between diagnosis and prevention. Long-term monitoring is increasingly supported by digital health technologies, including wearable devices that track cardiovascular parameters and telemedicine platforms that facilitate follow-up. These innovations are particularly relevant in resource-limited settings, where access to advanced imaging may be restricted but secondary prevention remains critical.

Finally, the overarching trend is toward integration and personalization. Stroke care is no longer defined by rigid time windows or uniform protocols; instead, it is guided by individualized imaging profiles, genetic predispositions, and dynamic risk assessments. MRI, MRA, and CDUS exemplify this shift, serving not only as diagnostic tools but as instruments of precision medicine. Their combined use ensures that patients receive care that is timely, targeted, and tailored, reflecting the broader evolution of stroke management in the modern era.

Conclusion

Multimodal imaging has become indispensable in the management of ischemic stroke, offering a comprehensive approach that integrates parenchymal, vascular, and extracranial assessment. The integration of MRI, MRA, and CDUS into clinical workflow reflects a layered approach tailored to different phases of stroke care. CT often serves as the initial modality in the hyperacute phase due to its speed and availability, primarily to exclude hemorrhage. However, MRI and MRA are increasingly utilized in extended time windows, refining treatment eligibility by distinguishing viable tissue from infarct core and mapping vascular occlusions. CDUS assumes prominence in the subacute and chronic phases, where the focus shifts to identifying and mitigating risk factors for recurrence. Together, these modalities ensure that patients benefit from rapid triage, precise intervention, and long-term surveillance, embodying a continuum of care that addresses both the acute event and its underlying causes.

Future directions in stroke imaging include hybrid approaches that combine modalities to provide integrated parenchymal and vascular information in a single session. Advances in portable imaging technologies are also expected to enhance accessibility, particularly in resource-limited settings where timely diagnosis remains a challenge. The development of faster MRI protocols, high-resolution MRA techniques, and contrast-enhanced CDUS methods will further improve accuracy and efficiency. Ultimately, the synergistic use of MRI, MRA, and CDUS represents the future of stroke imaging, bridging the gap between rapid diagnosis and personalized therapy, and ensuring that patients receive care that is timely, targeted, and tailored to their individual needs.

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I confirm that the manuscript is original, has not been published previously, and is not under consideration for publication elsewhere. All authors have contributed substantially to the work and approve the final version of the manuscript.

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