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Review article

High-resolution magnetic resonance vessel wall imaging in ischemic stroke and carotid artery atherosclerotic stenosis: A review

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ABSTRACT

Ischemic stroke is a significant burden on human health worldwide. Carotid Atherosclerosis stenosis plays an important role in the comprehensive assessment and prevention of ischemic stroke patients. High-resolution vessel wall magnetic resonance imaging has emerged as a successful technique for assessing carotid atherosclerosis stenosis. This advanced imaging modality has shown promise in effectively displaying a wide range of characteristics associated with the condition, leading to a comprehensive evaluation. High-resolution vessel wall magnetic resonance imaging not only enables a comprehensive evaluation of the instability of carotid atherosclerosis stenosis plaques but also provides valuable information for understanding the pathogenesis and predicting the prognosis of ischemic stroke patients. The purpose of this article is to review the application of high-resolution magnetic resonance imaging in ischemic stroke and carotid atherosclerotic stenosis.

1. Introduction

Ischemic stroke is a substantial global health challenge because of its high mortality and disability rates. The disease burden of ischemic stroke is increasing, acting as a serious threat to individuals and healthcare systems worldwide [1–3]. Atherosclerotic stenosis is one of the most frequent causes of stroke worldwide. The risk factors atherosclerotic stenosis include hypertension, diabetes, smoking, hyperlipidemia, and lifestyle factors [4]. In 2019, the five most dangerous factors for stroke worldwide were: high systolic blood pressure (resulting in 79.6 million disability-adjusted life-years (DALYs)), high body mass index (resulting in 34.9 million DALYs), high abdominal blood glucose (resulting in 28.9 million DALYs), environmental particulate matter pollution (resulting in 28.7

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million DALYs), and smoking (resulting in 25.3 million DALYs) [5]. The decreased incidence of ischemic stroke since 1999 is attributable to advancements in managing cardiovascular risk factors such as hypertension, diabetes, hyperlipidemia, obesity, and other related conditions. Additionally, preventive therapies targeting arrhythmia-induced ischemic stroke are crucial players in reducing the occurrence of ischemic stroke [6,7]. Between 2014 and 2015, the estimated annual cost of ischemic stroke in the United States was $45.5 billion and included various expenses such as healthcare costs, rehabilitation, medications, and lost productivity. The economic burden of ischemic stroke accentuates the importance of implementing prevention and effective management strategies for reducing both human and financial costs [8,9]. Age is a significant risk factor for ischemic stroke. While the incidence of ischemic stroke has recently been declining, the aging population has substantially increased the overall risk of lifelong ischemic stroke. Because people live longer, age-related factors and comorbidities cumulatively contribute to an increased likelihood of ischemic stroke [6,10,11]. Ischemic stroke is accountable for approximately 20% of all causes of death in China [12–14] (Fig. 1). A prospective cohort study of the World Health Organization (WHO) monitoring the trend and determinants of cardiovascular diseases and a retrospective study of the military cerebrovascular disease epidemiology collaboration group reported the following stroke-related statistics in China: Stroke accounts for 20% of urban deaths and 19% of rural deaths. The average age-standardized incidence and prevalence rates of all age groups are 116/100,000 and 3%, respectively [15]. Recent studies have reported increased prevalence and incidence rates of stroke [9,12]. Thus, stroke remains a substantial public health concern. Moreover, prevalence and mortality of stroke in different geographical regions are significantly different [2,16,17].

2. Carotid atherosclerotic stenosis and ischemic stroke

Carotid atherosclerotic stenosis is among the main causes of ischemic stroke and accounts for 18%–25% of all strokes. Conventionally, the severity of ischemic stroke is determined by the lumen stenosis degree and unstable plaques on the surface of the narrowed lumen [18,19]. The severity of carotid atherosclerosis stenosis is frequently regarded as a significant marker for evaluating the ischemic stroke risk. In numerous multicenter, large-scale randomized trials, the stenosis degree is used as a crucial inclusion criterion for evaluating the effectiveness of surgical and drug treatments against carotid atherosclerosis diseases [20–22]. Atherosclerotic stenosis in the extracranial segment of the internal carotid artery is currently managed using active drug treatment and surgical intervention in combination. Active drug treatment is typically the initial approach. Surgical treatment is recommended for patients with confirmed carotid artery stenosis (CAS) rates of more than 50%, as determined through imaging examination, who present evident clinical symptoms and/or unstable plaques. Additionally, patients with a CAS rate of 70% and stenosis-related distinct symptoms and signs, who experience ischemic stroke events despite receiving active drug treatment, may also be considered for surgery [23,24]. According to the 2021 European Stroke Organization guidelines, carotid endarterectomy (CEA) should be performed in patients with an asymptomatic CAS rate of 60%–99%. The ischemic stroke risk in these patients is higher if they receive only active drug treatment. Moreover, the guidelines also recommend CEA for patients with symptomatic CAS. CEA is strongly recommended for patients with 70%–99% stenosis, while it is recommended as a potential treatment for those with 50%–69% stenosis. More importantly, the optimal period of CEA treatment in patients with 50%–99% symptomatic stenosis is recommended to be as early as 2 weeks after the last ischemic event. Carotid artery stenting can be performed in patients aged less than 70 years with 50%–99% symptomatic stenosis [25,26]. In 1953, Michael Ellis DeBakey achieved a momentous milestone in the vascular surgery field by performing the world's first successful CEA to treat severe CAS and confirmed a normal carotid artery blood flow throughout the 19-year follow-up [27]. In 1954, ROB CG. et al. Reported cases of successful CEA treatment. In one such case, an elderly female patient who experienced

Fig. 1. Nearly 150,000 (5%) people died of ischemic stroke in the United States in 2016. Ischemic stroke is responsible for approximately 20% of all causes of death in China.

recurrent and frequent transient ischemic attacks (TIAs) underwent CEA. On angiography examinations, this patient presented severe CAS or even complete occlusion of the artery. These blockages were identified as the cause of her TIA episodes. The TIAs ceased after CEA [28]. Preoperative imaging of CAS is indeed crucial. Digital subtraction angiography (DSA) is an invasive procedure wherein a contrast agent is injected into the bloodstream, followed by X-ray imaging of cerebral arteries. DSA has traditionally been considered the gold standard for diagnosing and assessing CAS. Since the first DSA in Western countries in the late 1970s, this procedure has gained extensive global recognition. DSA has become an important tool for CSA diagnosis, evaluation, treatment, and prevention [25,29]. Numerous methods are currently available for CAS detection, including vascular ultrasound [30], computed tomography angiography (CTA) [31,32], magnetic resonance angiography (MRA) [33], transcranial doppler [34], and optical coherence tomography (OCT) [35]. These techniques are crucial players in evaluating CAS severity and plaque instability, which is essential for determining the risk of CAS-associated ischemic stroke. Furthermore, recent studies have emphasized the effectiveness of assessing the ischemic stroke risk by identifying vulnerable plaques through compositional analysis. Plaque composition plays a vital role in determining plaque stability and the likelihood of its rupture, which can lead to stroke [18,36,37]. Additionally, high-resolution vessel wall magnetic resonance imaging (HR-VWI) is a non-invasive technique that allows clear visualization of carotid atherosclerotic stenosis plaques. HR-VWI can be used to evaluate plaque characteristics and plaque instability and aid in preoperative safety assessment and treatment planning for CAS. This technique can also prevent CAS-associated ischemic stroke [38–40].

3. HR-VWI technology, application, and research

3.1. HR-VWI sequence

HR-VWI primarily involves the use several contrast techniques such as T1-weighted (T1W) black blood (BB) sequence [41–43], T2-weighted (T2W) [44] and proton density (PD)-weighted imaging [45], and a three-dimensional (3D) time-of-flight magnetic resonance angiography (TOF-MRA) sequence [46,47]. The T1W BB sequence suppresses the signal from flowing blood, which results in darker blood vessels, and enables improved visualization of the vessel wall and any abnormalities or plaques present. The T1W BB has been used in several studies, demonstrating the crucial role of HR-VWI in clinical practice [36,41,48,49]. The sequence offers detailed information about the vessel wall composition and structure, thereby helping clinicians assess plaque characteristics and identify vulnerable plaques associated with a higher stroke risk [50,51]. T2W and PD-weighted imaging provide additional information about the vessel wall. T2W imaging is sensitive to edema and inflammation within the vessel wall [52], while PD-weighted imaging is sensitive to plaque components such as lipid-rich cores and calcifications [45] (Fig. 2). These sequences allow for comprehensively assess the plaque composition and stability[45, 52, 53]. The 3D TOF-MRA sequence is used to visualize arterial blood flow. By using magnetic resonance techniques, this sequence creates high-resolution images depicting blood vessels and allows the identification of stenosis or occlusion regions. Because both the vascular anatomy and pathological changes occurring within vessel walls can be comprehensively understood with this sequence, it complements vessel wall imaging [46,47,53]. When these multiple contrast techniques are combined in HR-VWI, a thorough evaluation of carotid artery walls, including plaque detection, plaque characteristic assessment, and estimation of their risk for complications, becomes possible. This information aids in clinical decision-making, patient risk stratification, and personalized treatment planning [39,40]. In summary, HR-VWI requires the use of T1W BB, T2W and PD-weighted imaging, and 3D TOF-MRA. Complementary information provided by these contrast techniques about vessel walls, plaques, and blood flow enables a comprehensive assessment of carotid artery disease and aids in clinical management decisions [45,51,52,53]. According to the signal intensity of histology on different sequences, various pulse sequences in HR-VWI are

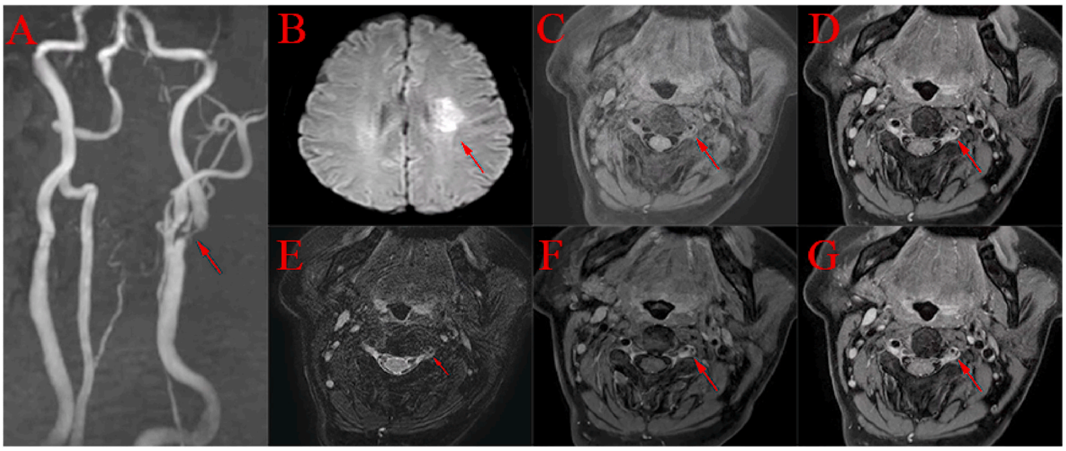

Fig. 2. A 62-year-old female, HR-VWI showed: MRA showed severe stenosis in the initial segment of the left internal carotid artery (**A**); Left basal ganglia infarction (**B**); T1W showed the presence of plaques in the vascular wall of the initial segment of the left internal carotid artery (**C**), and pre-contract and post-contract PDW showed a large area of lipid load (**D**, **G**); T2W showed severe stenosis of vascular wall and significant narrowing of vascular lumen (**E**); Post-contract T1W showed plaque enhancement (**F**).

associated with distinct advantages and disadvantages. These sequences can be used clinically based on their specific characteristics [54]. Evidence indicates that the HR-VWI results for CAS correlate closely and reliably with the pathological results of extracranial tissues [55]. HR-VWI uses advanced imaging techniques for vessel wall visualization and characterization and thus provides detailed information about plaque composition and morphology. HR-VWI has been extensively investigated and its results validated against those of histopathological analysis of surgically resected specimens [56,57]. A comparison of HR-VWI and histological findings revealed that the two techniques are strongly correlated. For instance, HR-VWI was highly accurate in identifying the presence of lipid-rich necrotic cores within plaques, a critical indicator of plaque vulnerability [45,58]. Results of histologically evaluated resected carotid artery plaques validated these findings [57,59]. In 2001, Yuan C et al. performed HR-VWI for CAS patients before operation, and judged the plaque with a lipid-rich necrotic core according to the different characteristics of plaque in 4 contrast weights (T1W, T2W, PD-weighted, and 3D TOF). Combined with the plaque tissue after CEA, found that HR-VWI had 85% sensitivity and 92% specificity [58]. In 2004, Chu B et al. used HR-VWI to evaluate intraplaque hemorrhage with high sensitivity (90%) and model specificity (74%) [56]. Of note, while HR-VWI is strongly correlated with histology, some limitations and discrepancies may still exist between the two modalities. Factors, such as tissue processing techniques and spatial resolution differences between imaging and histology, can lead to minor variations in results obtained using the two modalities. Nonetheless, the overall agreement between HR-VWI and histological findings supports the reliability and clinical relevance of HR-VWI in CAS assessment [56,60–62].

3.2. HR-VWI T1W BB sequence

The HR-VWI T1W BB sequence was developed in the 1990s and is widely used for cardiovascular imaging [63,64]. The 3D TOF-MRA sequence is commonly used in HR-VWI, in which blood flow is presented as a high-signal intensity. However, to specifically display the vessel wall and related diseases, T1W BB eliminates the blood flow signal in the lumen by applying different pulse settings and thus improves the display. Using a specific pulse setting in the T1W BB sequence, the bright signal from flowing blood is effectively suppressed and the surrounding vessel wall structure is highlighted. This technique can be used to evaluate various vascular lesions, such as atherosclerosis [41,50,51], aneurysms [49,65,66], and vasculitis [67,68]. Kurosaki Y et al found that the recurrence rate of acute cerebrovascular stroke in T1W BB high signal plaque group was 14.7% (5/34) [51]. The improved vessel wall visualization offered by the T1W BB sequence is beneficial in accurately evaluating the vessel wall thickness, plaque morphology, and any abnormalities or lesions present. 3D TOF-MRA and T1W BB can be combined to comprehensively evaluate blood flow characteristics and vascular wall pathology. This information integration allows the diagnosis and management of cerebrovascular diseases, enabling the assessment of stenosis severity, detection of vulnerable plaques, and monitoring of disease progression [36,50]. The clinical value and effectiveness of T1W BB were recently noted in the cerebrovascular imaging field. T1W BB remains a crucial tool for evaluating and characterizing vascular diseases non-invasively, thereby providing a valuable understanding of the blood vessel structure and integrity [50,51]. In T1W BB, the blood flow is deliberately suppressed to display a low signal within the lumen, mostly by using the flow saturation method applied in the blood inflow direction. However, this method can sometimes lead to flow artifacts that manifest as high signals indicating the presence of flowing blood [69,70]. Flow artifacts can result from various factors, including turbulent or complex flow patterns, imaging at high flow velocities, or inadequate flow suppression. Flow artifacts can obscure vessel wall visualization and hinder the accurate assessment of vascular pathologies. Several strategies can be employed to prevent flow artifacts, such as optimizing the flow saturation pulse parameters, adjusting the timing of the acquisition, and employing parallel imaging techniques to reduce image distortion [71,72]. Additionally, advanced motion-sensitized driven equilibrium preparation techniques can be executed to further suppress the blood flow signal and minimize flow artifacts. Radiologists and technologists performing HR-VWI must be aware of flow artifact-associated challenges and must employ appropriate techniques to minimize the impact of these artifacts [73,74]. Implementation of optimized imaging protocols and advanced techniques can help improve the quality of HR-VWI images, visualize vessel walls clearly, and evaluate vascular diseases more accurately. Continued research and advancements in HR-VWI technology are underway, aiming to further enhance flow suppression methods, reduce artifacts, and improve overall image quality. This would allow a more reliable and robust assessment of vascular pathologies in clinics [71–74]. The BB dual inversion recovery (BB-DIR) technique is widely employed as the primary BB imaging method [75,76]. In this technique, the sequence incorporates a non-selective 180° inverted pulse and a spatially selective 180° pulse. BB-DIR can carefully select an appropriate inversion time and thus effectively suppress blood flow signals, resulting in improved vessel wall visualization. BB-DIR is valuable in assessing various vascular conditions, including atherosclerosis and other vascular pathologies. This technique allows heightened differentiation between the vessel wall and lumen by nullifying the blood flow signal. When blood flow signals are suppressed, plaque morphology and other abnormalities within the vessel wall can be easily identified and characterized [77,75,76]. Building upon the success of BB-DIR, BB quadruple inversion recovery (BB-QIR) technology was developed. BB-QIR further refines BB imaging by including additional inversion pulses and offering improved blood flow suppression and better image quality [78,79]. The multiple inversion pulses used in BB-QIR allow it to enhance the contrast between the vessel wall and surrounding tissues, which increases the accuracy of diagnosis and evaluation of vascular diseases [80,81]. BB imaging in clinical settings has advanced because of the significant contribution made through the development and implementation of BB-DIR and BB-QIR. These two methods are effective in suppressing blood flow signals and allowing high-resolution visualization of vessel walls, thereby resulting in enhanced detection and characterization of various vascular pathologies. Ongoing studies aim to refine these techniques and explore their potential applications in different clinical scenarios [79,82]. Both BB-DIR and BB-QIR have exhibited superior blood signal suppression in vascular imaging. Compared with other imaging techniques, these techniques offer an improved spatial resolution, signal-to-noise ratio contrast, and reduced flow artifacts.

3.3. HR-VWI 2D and 3D scans

Early use of two-dimensional (2D) HR-VWI scans is effective for comprehensively evaluating plaque components. This imaging modality provides details about various aspects of plaque composition within the vessel wall [73,83–85]. Prospective cohort studies have demonstrated the usefulness of 2D HR-VWI in evaluating unstable carotid plaques and preventing ischemic stroke [86,87]. However, certain limitations of this technology restrict its effective use in routine clinical practice. One such limitation of 2D HR-VWI is its small scanning coverage, which allows imaging of only a limited portion of the vessel wall at a time. Because of this restricted coverage, multiple scans at different levels may be required to comprehensively assess the entire vessel, leading to increased examination time and probable challenges in image fusion and interpretation [88]. Moreover, the increased scanning time required to obtain high-resolution multi-level images also hampers efficient 2D HR-VWI implementation in clinical settings. This is because prolonged scanning times can cause inconvenience to patients and may result in motion artifacts, compromising image quality and reliability. This limitation poses real-world difficulties, particularly in busy clinical environments requiring quick and streamlined imaging protocols. To address these limitations, efforts have been made to develop and implement alternative techniques, such as 3D HR-VWI [83,89,90]. 3D HR-VWI offers a larger vessel wall coverage in a single scan, thereby reducing the requirement for multiple acquisitions and the overall examination time. This advancement can overcome the limitation of small scanning coverage of 2D HR-VWI [91,82]. Furthermore, the plane slice resolution in the 2D HR-VWI BB currently used in carotid artery MR angiography research is constrained. Because of partial volume effects, this constraint can impede the accurate detection and consistent measurement of plaque components. To overcome these limitations, 3D imaging techniques and advanced post-processing algorithms have been adopted. The partial volume effects can be minimized using 3D HR-VWI BB imaging and reconstruction methods. This is because these methods can provide higher spatial resolution and enable volumetric assessment of carotid plaques (Fig. 3). Furthermore, automated image registration and fusion algorithms are being created to improve the alignment of sequential images, thereby ensuring

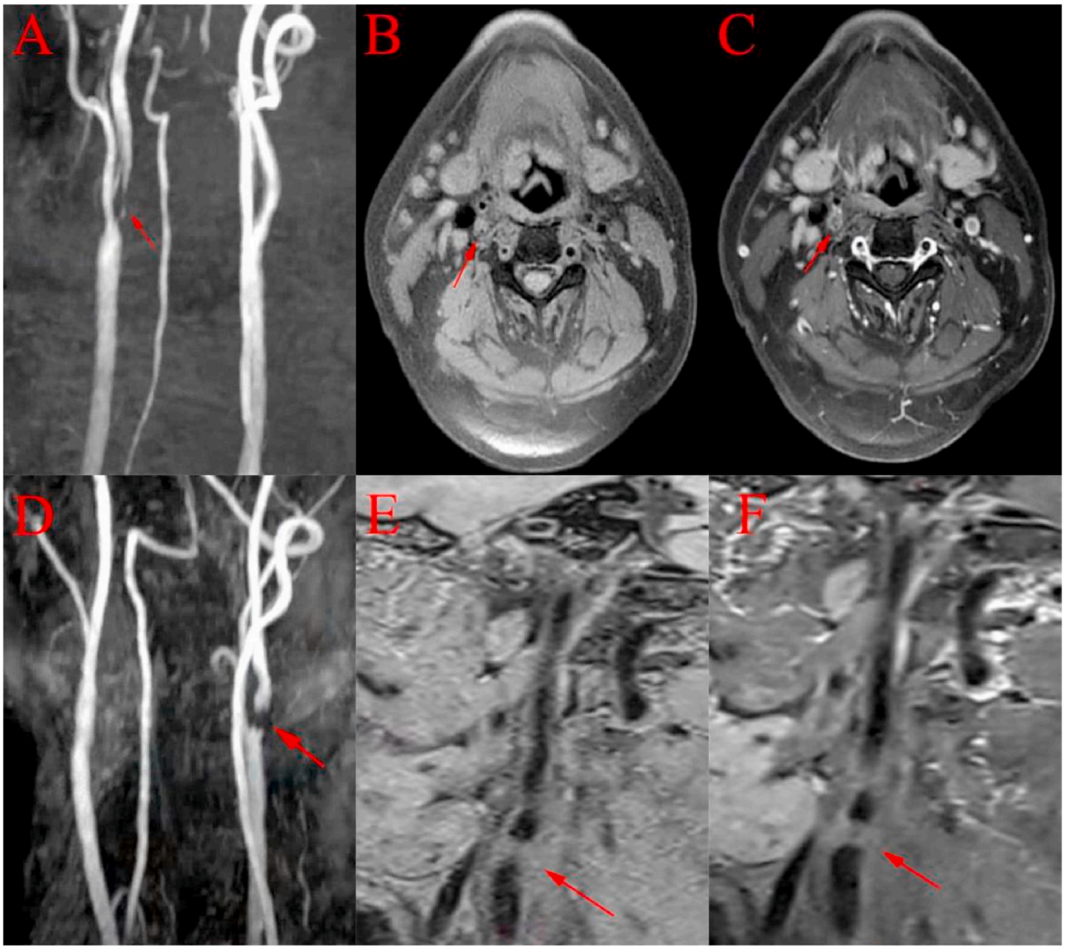

Fig. 3. **Case 1**: A 60-year-old male 2D HR-VWI showed: MRA showed stenosis in the initial segment of the right internal carotid artery (**A**), pre-contract 2D T1W showed the presence of plaques with clear boundaries (**B**), and post-contract 2D T1W showed partial enhancement of plaques (**C**). **Case 2**: A 59-year-old male 3D HR-VW showed: MRA showed stenosis in the initial segment of the left internal carotid artery(**D**), pre-contract 3D T1W showed plaque blockage (**E**), and post-contract 3D T1W showed enhancement at the edge of the plaque.

more accurate and reliable longitudinal measurements [83,92]. By addressing the limited resolution of plane slices in 2D HR-VWI BB and mitigating errors due to changes in the slice position and alignment, the accuracy and reproducibility of carotid artery MR angiography studies can be improved. These advancements provide a more complete understanding of plaque characteristics and aid in developing effective strategies for preventing and treating carotid artery disease [93–95]. Overall, despite the advantages of 3D HR-VWI, longer imaging times currently limit the extensive routine use of this technique in clinics. Efforts are being taken to make 3D HR-VWI more practical. Strategies are being explored to optimize imaging protocols, acquisition parameters, and post-processing algorithms to reduce scanning time while maintaining high image quality. By minimizing the imaging duration, these advancements aim to increase the clinical feasibility and applicability of 3D HR-VWI. However, ongoing research and technological advancements can potentially overcome limitations and make these techniques more accessible for everyday clinical use [46,83]. Quantifying plaque enhancement [37,50], plaque burden [36,96], and positive remodeling [97,98] with HR-VWI can offer valued insights into atherosclerotic plaque characteristics, and these insights are comparable to those obtained by assessing vascular stenosis through angiography. Plaque morphology can be precisely measured only in the presence of high isotropic resolution in all three spatial dimensions [99,100]. Currently, the application of 3D multi-echo recalled gradient echo (3D-MERGE) vascular wall imaging, developed using a 3D motion-sensitive driving balance technique, has been scientifically validated to offer high-resolution isotropic imaging and extensive coverage within a short scan duration. This advanced technology can be used to precisely assess and measure plaque burden [73,100–102]. Moreover, enhancement differences within the vascular wall and irregular surface are considered advanced carotid artery lesions. Duygu Baylam Geleri et al. demonstrated that 3D-MERGE can scan accurately and screen late-stage carotid artery lesions [73,90,103].

4. HR-VWI and ischemic stroke

HR-VWI has been confirmed to be a novel and practical clinical tool for diagnosing ischemic stroke [36,37,94,104,105]. This technique can effectively identify unstable plaques and predict ischemic stroke occurrence [94,105]. In 2023, Wu G et al found that T1-weighted fat-suppressed images and intracranial hyperintensities coexisting on CAS (HR, 6.12; 95% CI, 2.52-14.82; $p = 0.001$) were independent imaging predictors of stroke recurrence through a prospective study [94]. In addition, Tian B et al found that lower plaque eccentricity (OR 0.18, 95% CI, 0.04-0.96, $p = 0.04$) and higher enhancement ratio (OR 3.57, 95% CI, 1.02-12.48, $p = 0.04$) were independently associated with in stent restenosis [105]. The findings of these studies highlight the valuable role of HR-VWI in ischemic stroke management and prevention [36,37,106]. Ischemic stroke is usually caused by CAS[18.19]. With HR-VWI, the vascular wall can be imaged and visualized in detail, offering valuable information about plaques, stenosis, or other abnormalities that may lead to stroke [18,37,45,77]. Using HR-VWI, vascular wall characteristics, such as plaque composition, vulnerability, and rupture, can be assessed. In 2023, Ma X et al used HR-VWI to evaluate the relationship between plaque indicators and intraprocedural stent thrombosis (IPST), and found that patients with IPST had higher plaque enhancement index [107]. In addition, Zhang J et al reported in 2024 that atherosclerotic stenosis and occlusion of the internal carotid artery were significantly associated with diffuse wall thickening of the upstream artery wall [108]. This information can help identify patients with a high stroke risk and apply targeted preventive measures [36, 37, 109]. HR-VWI can also aid in determining the cause of stroke because different potential mechanisms (such as atherosclerosis [51] or vasculitis [110]) can be identified through this technology. Moreover, HR-VWI is beneficial in selecting the appropriate treatment strategy [111]. For example, if unstable plaques or fragile vascular walls are noticed, active medical management or interventional procedures may be required to prevent future strokes [1,112,113]. In conclusion, HR-VWI has a key role in understanding stroke pathophysiology and etiology, identifying high-risk individuals, and guiding personalized treatment. It improves our knowledge of the relationship between vascular wall abnormalities and stroke and ultimately results in better stroke prevention and management [94,104,105,112]. HR-VWI thus holds promising prospects for its application in ischemic stroke diagnosis and prevention. In current medical practice, HR-VWI images are a dependable foundation for determining the specific etiology and pathogenesis of ischemic stroke in each patient. Moreover, these images help select personalized prevention and treatment approaches. Recently, Wu XB et al. used HR-VWI combined with hemodynamic indicators to analyze the relationship with ischemic stroke, and found that plaque enhancement and wall shear stress ratio were significantly associated with ischemic stroke [113]. This demonstrates the remarkable contributions of HR-VWI in improving patient outcomes and directing tailored interventions for ischemic stroke [94, 114–116].

5. HR-VWI and CAS

The diameter of the carotid artery lumen is typically within 5–7.5 mm, with the vascular wall having a thickness of approximately 1–2 mm [117,118]. Although widely used imaging examinations such as CTA [31,32] and vascular ultrasound [119,120], are effective in assessing the CAS degree, they do not allow a clear visualization of the carotid artery vascular wall or offer detailed characterization of CAS-associated complex atherosclerotic plaques. As early as 1992, a study explored the application of HR-VWI for assessing blood vessel walls [121]. In 2001, Yuan C et al. used HR-VWI to investigate carotid plaques. They compared the plaques of patients who underwent CEA with the results of preoperative HR-VWI imaging and postoperative pathology. They found that the signal characteristics observed in HR-VWI were consistent with the histopathological findings. Moreover, HR-VWI was highly sensitive and specific in identifying various components of carotid artery plaques [56]. Previous pathological studies have reported the enhancement of atherosclerotic plaques indicates localized plaque inflammation. The imbalance of inflammatory processes within the plaque microenvironment is a contributing factor in atherosclerosis progression [56,60]. A potential association between gadolinium-enhanced MR contrast agents and inflammation has been demonstrated [122]. In animal experiments, plaques exhibiting high enhancement rates were characterized by significantly increased macrophage infiltration [60]. Furthermore, the degree of enhancement was positively correlated with the magnitude of the inflammatory response within the plaques [60]. Using mouse models on a high-fat diet, Hellberg et al. observed that both plaque burden and macrophage presence significantly increase in aortic plaques. This finding suggested plaque burden is positively associated with inflammatory processes, further emphasizing the involvement of inflammation in atherosclerosis development and progression [123]. Calcagno C et al. reported a correlation between plaque burden and local inflammation in experimental atherosclerotic plaques. Their results suggested that an increased plaque burden is associated with heightened levels of local inflammatory activity within these plaques, further supporting the notion that inflammation is a crucial player in atherosclerosis pathogenesis [124]. Through a systematic review, Amirati E et al. explored the inflammatory biomarkers associated with high atherosclerotic plaque burden. They identified several inflammatory biomarkers exhibiting significant associations with increased plaque burden. They highlighted potential molecular targets for assessing and monitoring atherosclerosis progression [125]. The application of HR-VWI in the investigation of CAS plaques has recently been growing. HR-VWI allows clear visualization of various characteristics of CAS plaques, including plaque enhancement [50,93], plaque burden [36,126], and plaque area [36,127]. These observations are valuable for screening and identifying risk factors associated with unstable plaques. HR-VWI contributes significantly to our understanding of plaque vulnerability and helps in assessing stroke risk in individuals with CAS [38–40,51,93]. With HR-VWI, utilizing either 1.5T or 3.0T MRI technology, sectional images of CAS can be acquired [57,128]. Through these images, researchers and clinicians can measure arterial wall thickness, assess lumen area, and observe the morphological characteristics of atherosclerotic plaques. They can gain valuable insights into atherosclerosis-associated structural changes and the accompanying plaque formation. With this non-invasive imaging technique, a detailed assessment of the vascular wall and the diagnosis and management of CAS are possible [39,40,73,98,112]. To thoroughly evaluate the characteristics of atherosclerotic plaques, a contrast agent is often injected to enhance the image scan quality. By analyzing the enhancement patterns within the arterial wall and atherosclerotic plaques, high-quality and reproducible results can be obtained. This improved scanning technique can be used to precisely assess plaque composition, vulnerability, and extent, resulting in improved diagnostic accuracy and informed decision-making regarding appropriate treatment strategies for patients [36,37,73]. Therefore, using HR-VWI for observing the characteristics of carotid atherosclerotic plaques and analyzing and evaluating these characteristics along with patients' clinical data is of utmost importance. With this comprehensive approach, an evidence-based medicine foundation can be established for evaluating and predicting unstable atherosclerotic plaques [36,129,130]. Integration of imaging findings with relevant clinical information can improve the ability of clinicians to identify high-risk plaques, make treatment strategy-related informed decisions, and provide personalized care for patients with carotid artery disease. This evidence-based approach contributes to improving patient outcomes and reducing cerebrovascular events associated with unstable carotid atherosclerotic plaques.

6. Development direction of HR-VWI

HR-VWI can be applied in various disease conditions [38,39,45,48,49]. For extensive clinical application of HR-VWI, several key directions should be considered, including enhancing the clarity of HR-VWI images, standardizing the definitions of various image characteristics, and establishing standardized quantitative measurement techniques [36,95,131,132]. With image clarity, vascular structures and pathological changes can be visualized more clearly, facilitating accurate diagnosis and assessment. When characteristic definitions are standardized, interpretation and comparison of HR-VWI findings across different patients and research studies can be consistent [36,37]. Additionally, the establishment of standardized quantitative measurements allows for the objective and reproducible assessment of disease severity and progression [36,105]. These aforementioned advancements are crucial for the use of HR-VWI as a routine clinical tool in the future, thus enabling better patient management and improved outcomes [133]. Future research directions are aimed at enhancing the capabilities of HR-VWI. These directions include but are not limited to, improving the resolution of scanned images, enhancing tissue contrast, reducing scanning time, and exploring the fusion of vascular wall imaging characteristics derived from HR-VWI with hemodynamic factors, such as vascular wall shear forces [49,134]. Scanning time must be shortened to make HR-VWI more clinically feasible, and reduce patient inconvenience and the burden on healthcare systems [135]. Furthermore, the fusion of vascular wall imaging characteristics with hemodynamic factors can aid in comprehensively understanding atherosclerosis pathophysiology, possibly leading to improved risk stratification and personalized treatment approaches. These research directions are promising for advancing the HR-VWI field and expanding its role in clinical practice [134,135,136]. With the accumulation of multi-parameter data obtained through HR-VWI, artificial intelligence (AI) can be integrated to provide more reliable and accurate data for assessing CAS and predicting stroke risk [137,138,139]. AI algorithms can analyze large datasets and extract meaningful patterns and associations, which may not be easily discernible to human observers. Sophisticated models that can accurately classify different plaque characteristics, quantify stenosis severity, and predict the risk of future stroke events can be developed using AI [137,140]. This integration of AI with HR-VWI can potentially enhance clinical decision-making, improve patient risk stratification, and guide therapeutic interventions. However, these AI-driven approaches must be validated and refined in the future before their prevalent clinical implementation [137, 141]. HR-VWI technology has gradually matured because of the continuous advancements in magnetic resonance hardware and software. These advancements have optimized imaging techniques, and the combination of various pulse sequences has improved the effectiveness of blood flow suppression. HR-VWI development has witnessed remarkable improvements in hardware and software aspects. Advances in magnetic resonance hardware, such as high-field-strength magnets and specialized vascular coils, have allowed high-resolution imaging of carotid arteries [102,142]. HR-VWI has been applied to MRI equipment with magnetic field strengths of 1.5T [57,128], 3.0T [43,50], and 7.0T [47,53]. Lower magnetic field strengths (such as 1.5T) are usually suitable for most clinical applications because they are relatively inexpensive and easy to operate. However, lower magnetic field intensity may result in slightly lower image resolution. Higher magnetic field strengths (such as 3.0T and 7.0T) can provide higher image resolution and better contrast, as the higher the magnetic field strength, the higher the signal strength. In 2023, Bai X et al. used 7.0T MRI to observe arterial plaques and found that plaque features from 7.0T HR-VWI showed good diagnostic accuracy in determining the occurrence of subcortical infarction [53]. HR-VWI can achieve high accuracy and repeatability in evaluating various parameters related to plaque assessment and vascular wall characteristics. However, further research and validation studies are warranted to ensure the reliability and clinical utility of HR-VWI before its extensive implementation in routine clinical practice.

7. Limitations of HR-VWI

HR-VWI is widely used in the medical field for observing and diagnosing human structures and lesions [38–40,48,49]. Because HR-VWI can provide detailed and high-quality images of blood vessels, this technique has significantly allowed the understanding and management of various vascular pathologies[55, 56, 60, 123, 124]. Despite its substantial advantages, some limitations remain associated with this technique: first, the time cost is relatively high. In HR-VWI, longer scanning time is usually required to acquire high-resolution images, which may be inconvenient or unsuitable for certain patients, such as those who cannot remain stationary or have difficulty breathing. Additionally, prolonged scanning times for acquiring images can significantly increase the risk of motion artifacts during imaging. These artifacts occur when the patient or the imaging equipment moves, resulting in blurred or distorted images. Motion artifacts can obscure fine details, and therefore, healthcare professionals find an accurate interpretation of acquired images more challenging, which potentially results in misdiagnosis or missed abnormalities. Furthermore, spatial resolution, which is the ability to distinguish and accurately represent fine details in an image, is limited in high-resolution imaging. This is because more data points are required to construct the image in high-resolution imaging, which results in a trade-off between image quality and spatial resolution. For instance, higher spatial resolution is crucial for the accurate visualization and analysis of small tissue structures, such as tiny lesions or intricate blood vessels. However, the current technology may be unable to meet these requirements for high-resolution imaging, and therefore, compromises on the spatial resolution front may be required. Consequently, certain fine details within the images may not be visually clear or appropriately resolved, which may lead to missed diagnoses or limitations in evaluating specific conditions. Therefore, advanced imaging technologies that can achieve higher spatial resolution without compromising image quality must be developed in the medical field. Similarly, when applying HR-VWI, demands equipment and technology are stringent. To achieve high-resolution magnetic resonance imaging, specialized equipment that is highly sensitive to magnetic resonance signals is required. Additionally, specific imaging techniques are employed to obtain accurate and detailed results. These requirements translate to markedly high costs of the necessary equipment and its proper maintenance. Moreover, HR-VWI is complex, and so, only professionals with extensive technical and operational experience can effectively operate and interpret the imaging data obtained. Thus, widespread HR-VWI implementation is a considerable challenge because of the substantial financial investment required and the scarcity of trained personnel. Furthermore, HR-VWI findings must be integrated with other clinical information and patient characteristics. To comprehensively evaluate CAS, a multidisciplinary approach, involving collaboration between radiologists, neurosurgeons, cardiologists, and neurologists, is required. This team can consider the patient's symptoms, risk factors, and overall cardiovascular health to make informed decisions regarding the most appropriate treatment options available for each individual [133]. In summary, continuous research is essential to improve HR-VWI scanning efficiency and diagnostic accuracy and facilitate its widespread clinical use.

8. Conclusion

HR-VWI remains a crucial tool in medical diagnosis that provides accurate information about CAS and guides treatment and surgical decision-making. It also has crucial preventive and therapeutic effects on ischemic stroke. Although HR-VWI has some limitations, ongoing technological advancements are expected to address them to a certain extent.

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Li-Xin Huang: Writing – review & editing, Writing – original draft, Conceptualization, Hui Wang, Funding acquisition, Supervision, Writing – review & editing. **Xiao-Bing Wu:** Writing – original draft, Conceptualization. **Yi-Ao Liu:** Writing – original draft. **Xin**

Guo: Writing – original draft. **Chi-Chen Liu:** Writing – original draft. **Wang-Qing Cai:** Conceptualization. **Sheng-Wen Wang:** Writing – review & editing, Validation, Funding acquisition, Data curation, Conceptualization. **Bin Luo:** Writing – review & editing, Writing – original draft, Visualization, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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