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SPECIAL REPORT

Expert consensus on intracranial vessel wall MRI in cerebrovascular disease: Society for Magnetic Resonance Angiography recommendations

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Abstract

In recent years, the clinical interest and research evidence of intracranial vessel wall MR imaging (iVWI) in vasculopathy lesion detection and characterization have made the technique a mainstay of patient care. Employing techniques with sufficient blood signal suppression (black blood) allows for direct visualization of lesions in the vessel wall itself, and facilitates the detection, evaluation, diagnosis, and differentiation of various cerebrovascular diseases. Clinical applications have extended rapidly to include multiple indications and pathologies, but the level of evidence and confidence varies for each of these indications and needs to be stratified and updated. On the other hand, a recent academic survey emphasized the need for additional technical and educational support in the neuroradiology community. The aim of this article is to provide expert consensus from the Society for Magnetic Resonance Angiography (SMRA) working group members for current clinical practice of iVWI with three levels of recommendation and to explore possible future clinical research applications.

Key Points

Question *By direct visualization of the intracranial vessel wall, iVWI facilitates the detection, evaluation, diagnosis, and differentiation of various cerebrovascular diseases.*

Findings *Updated evidence indicates that iVWI is now useful for many clinical indications, although challenges remain in certain settings.*

Relevance statement *With the advancement of hardware, improved resolution, innovation of sequences, post-processing, and analysis, iVWI has become promising in a variety of clinical indications to facilitate the evaluation and potentially improve the management of multiple cerebrovascular diseases.*

Keywords Magnetic resonance imaging, Intracranial vessels, Stroke

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Introduction

There is growing clinical interest in applications of direct visualization of the vessel wall using high-resolution intracranial vessel wall MR imaging (iVWI). iVWI is achieved using black-blood MRI, where the intraluminal blood signal is suppressed, thereby allowing the vessel wall to be seen. Demand for clinical vessel wall MRI is increasing, prompting experts from the American Society of Neuroradiology (ASNR) to publish consensus recommendations in 2017, listing indications of iVWI with three different levels of recommendation [1]. However, in the interval since publication of this important paper, there have been significant technical improvements and growth in the body of literature, further characterizing and supporting clinical applications. The ASNR published a survey in 2022 (411 valid responses), finding that more than 50% of neuroradiology groups use iVWI for intracranial vasculopathy characterization and differentiation, and 40.6% believe that iVWI has led to an impact on patient management at their institutions. For those not performing this technique, limited interpretation expertise (53.1%), paucity of technical support (46.4%), and lack of knowledge of clinical applications (50.5%) were the most common reasons, emphasizing the need for additional technical and educational support [2].

The Society for Magnetic Resonance Angiography (SMRA), a society comprised of vascular MR experts, wrote this article to help further educate radiologists, technologists, researchers, and referring clinicians in related specialties on the clinical value of iVWI and how it may potentially improve the evaluation and management of intracranial vascular diseases. We review the technical advantages of iVWI with recommendations for protocols, followed by a detailed discussion of the utility and applications of iVWI in the assessment of intracranial vascular diseases with three levels of recommendation.

Consensus methodology

The recommendations presented in this report were developed by a working group of SMRA members with clinical and technical expertise in iVWI. The panelists included 15 experts (11 from the USA/North America, 3 from China/Asia, and 1 from France/Europe) with an average of 16 years of experience and 39 published journal articles in vessel wall imaging. The following electronic databases were assessed: Ovid Medline, PubMed, Web of Science Collection (2015–2025, with minimal overlap with the last version of expert consensus in 2017). English articles were searched with the following keywords: (vessel wall imaging OR vessel wall magnetic resonance imaging OR vessel wall MRI) AND (intracranial OR middle cerebral artery OR basilar artery) in either Title or Abstract. Relevant literature was supplemented with extensive cross-checking of the reference, including several articles naming "Higher-Resolution MRI", "Black-Blood MRI", or "Arterial Wall Imaging". Expert opinions were shared through email discussions and teleconferences in an interactive fashion.

Technical implementation

The most important technical requirements of iVWI are (1) high spatial resolution while maintaining an adequate signal-to-noise ratio (SNR); (2) sufficient suppression of blood and cerebrospinal fluid signal; and (3) multiplanar 2D acquisition or isotropic 3D acquisition with larger coverage (ideally the whole brain) and multiplanar reconstructions. Appropriate acceleration techniques could be applied to reduce the scan time to a clinically acceptable level.

Hardware

Higher field strength is beneficial for iVWI because of high SNR. Although some early studies used 1.5-T MR for iVWI, 3.0-T MRI is now more extensively used both for clinical applications and research. The recent utilization of 7.0-T MRI scanners has resulted in excellent image quality for characterizing intracranial vasculopathies in some studies [3, 4]. In clinical settings, it is recommended to employ 3.0-T scanners. An example of the comparison between 3 T and 7 T in a patient with intracranial plaque is shown in Fig. 1. 7.0-T MR is still recommended for research use due to its limited availability and concerns about field inhomogeneity artifacts.

In general, within a certain field of view, coils with a higher number of channels lead to increased SNR. A study showed that a 32-channel head coil increases SNR up to 3.4-fold in the cortex and up to 1.4-fold in the corpus callosum compared to an 8-channel head coil [5]. To perform combined imaging of intracranial and extracranial vessel walls, special joint head and neck coils could be considered [6]. The commonly available head and neck coils used for clinical head and neck contrast-enhanced MRA can also be used for iVWI with good image quality.

Spatial resolution

3D isotropic scans are preferred, given the variable course of the intracranial arteries. A spatial resolution of 0.5 mm isotropic was recommended in the previous consensus [1] and is now routinely used at multiple institutions, as it improves delineation of vessel wall boundaries and enables more accurate assessment of stenosis and remodeling. However, slightly lower resolutions (0.6–0.7 mm) may increase conspicuity of wall enhancement due to volume averaging, although at the expense of reduced ability to characterize wall morphology. Importantly, higher spatial resolutions also come with longer scan

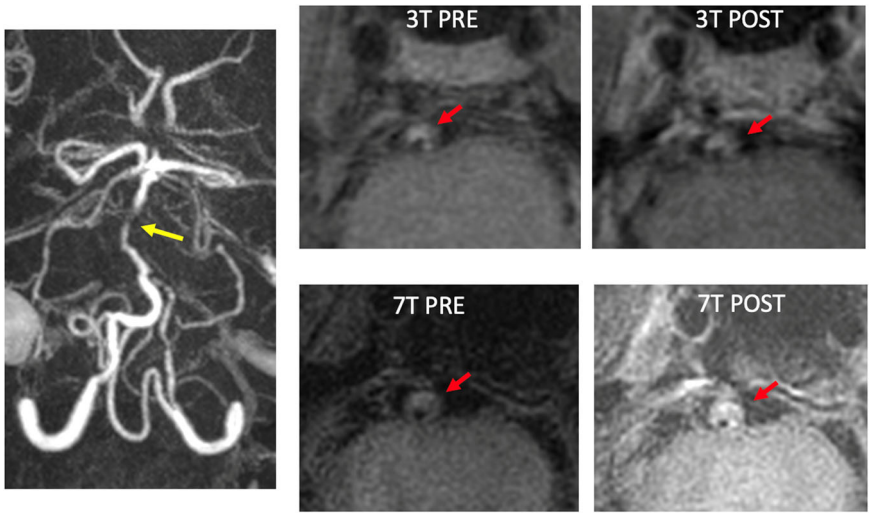

Fig. 1 Different flow suppression techniques. A patient with intracranial aneurysms showed flow artifacts and wall enhancement on traditional post-contrast iVWI images (SPACE, Siemens, 0.6 mm isotropic resolution). In the same aneurysm, motion-sensitized driven-equilibrium (MSDE) and delay alternating with nutation for tailored excitation (DANTE) blood suppression techniques reduced the flow artifacts and some of the fake enhancement of the wall

times, so parameter selection should balance diagnostic priorities with clinical feasibility.

Sequences and protocols

3D fast spin-echo or turbo spin-echo sequences with variable-flip-angle refocusing pulse trains are the method of choice for iVWI [7], with high scan efficiency (due to long echo train while reducing the signal decay) and inherent black-blood effect (due to intra-voxel phase dispersion among moving spins). Major equipment manufacturers have offered optimized versions of 3D TSE in their standard brain protocols, such as CUBE (GE), SPACE (Siemens), VISTA (Philips), 3D MVOX (Canon), isoFSE (Hitachi), and MATRIX (United Imaging). Flow artifacts can be present when there is slow flow or in-plane flow, especially for post-contrast scans, and additional blood suppression methods are recommended. Several preparation pulse techniques for blood suppression are available, such as motion-sensitized driven-equilibrium (MSDE) and delay alternating with nutation for tailored excitation (DANTE). An example is shown in Fig. 2. Both MSDE and DANTE can achieve strong blood suppression performance, and the parameters need to be optimized for a specific protocol and application. DANTE has the advantage of minimal alterations of tissue contrast and low sensitivity to magnetic field inhomogeneity, but it is limited in long prep-pulse time (> 100 ms). MSDE has the advantage of a short prep-pulse time (less than 50 ms), and it is available commercially on Siemens and GE MRI scanners. But MSDE has additional T2 weightings and decreases SNR. There is still no study comparing MSDE and DANTE's diagnostic performance, and future studies are needed. It is recommended that either MSDE or DANTE be used when available.

Recommendations for parameters and contrasts are listed in Table 1.

A minimal protocol should include T1 pre-contrast iVWI. Post-contrast T1 is highly recommended as contrast enhancement is a critical biomarker of vessel wall pathology. Pre contrast T2 weighted iVWI is optional [8]. Post T1 can be performed immediately after contrast injection to save total scan time, or can be delayed when there are other post-contrast non-vessel wall imaging sequences [9]. Either slab selective (covering the majority of the circle of Willis) or whole brain imaging can be performed.

Acceleration techniques are commonly used in iVWI, including partial Fourier, parallel imaging, compressed sensing, or deep learning [10, 11]. Joint intracranial and carotid vessel wall imaging can be performed without increasing scan time using head-neck coils [12]. An example is shown in Fig. 3.

Image analysis

The established method of post-processing of iVWI usually relies on a manual approach. Newer semi-automated quantitative tools now enable multi-timepoint, multi-contrast analysis of iVWI [13]. Quantitative measurements include plaque thickness and burden, enhancement ratio, and the remodeling index. For stenotic disease, the slice with the greatest severity (i.e., maximal lumen narrowing) should be chosen for

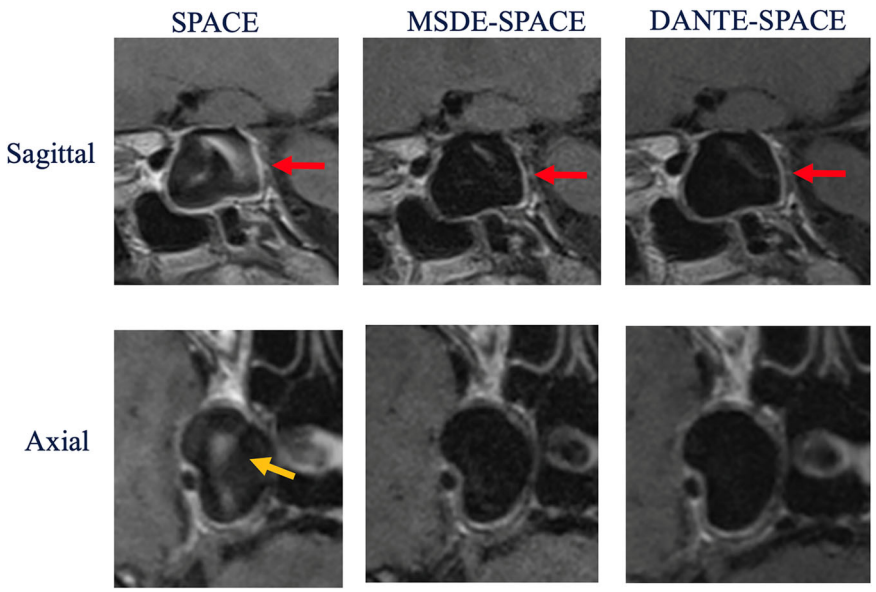

Fig. 2 Comparison between 3-T and 7-T iVWI in a patient with intracranial plaque. Basilar artery stenosis is shown in MRA. 7 T shows higher image quality and higher resolution of the plaque than 3 T

Table 1 Recommendations of scanning sequences and parameters for iVWI

	2D iVWI		3D iVWI	
Sequence	T1/CE-T1	T2	T1/CE-T1	T2
TR (ms)	800–1000	3000–4000	800–1000	2000–2500
TE (ms)	10–20	50–60	20–30	50–60
FOV (mm^2)	200 × 200	200 × 200	200 × 200	200 × 200
Echo train length	10	20	40-50	60-80
In plane resolution (mm^2)	0.4 × 0.4	0.4 × 0.4	0.5–0.7	0.5–0.7
Slice thickness	2	2	0.5–0.7	0.5–0.7
Number of slices	10–15	10–15	120–200	120–200
Scan time (min)	3–5	3–5	4–8	4–8

measurement. For larger lesions such as aneurysms, multiple slices (for instance, an average of three slices [14]) can be included for 2D sequences, or 3D analysis can be employed [15]. An example of 3D centerline analysis is shown in Fig. 3.

In terms of repeatability, studies have shown good inter-rater and scan-rescan reproducibility of quantitative measurements on iVWI, reporting an intraclass correlation coefficient ranging from 0.78 to 0.98 [16–18]. The identification of qualitative features such as plaque existence, plaque surface irregularity, intraplaque hemorrhage, and enhancement also exhibited sufficient intraobserver and interobserver agreement, with a kappa ranging from 0.58 to 0.96 [16, 18, 19].

Furthermore, recent research showed the feasibility of automatic segmentation and analysis of the vessel wall morphology. Deep learning-based methods could be employed, and a VWI-dedicated automated processing pipeline could be developed for end-to-end evaluation [20]. A radiomic approach has been attempted to identify acute/sub-acute symptomatic plaques, showing a high area under the curve, but it should be further validated [21]. Clinical studies also generated 3D enhancement color maps for intracranial atherosclerosis [22], saccular aneurysms [23], and fusiform aneurysms [24]. These methods are still being actively researched and validated.

Three levels of recommendations for clinical practice are summarized in Table 2 and explained below. The comparison between the recommendations in the current consensus and the ASNR 2017 consensus is listed in Supplemental Table 1.

Indications in which iVWI is likely useful

To identify symptomatic, nonstenotic disease of the intracranial arteries, and to determine the plaque location relative to branch artery ostia

Over the past two decades, with an increasing recognition of the role of vascular remodeling and the clinical significance of atherosclerotic plaque features, imaging of intracranial atherosclerosis has shifted from indirect assessment of luminal stenosis toward more direct assessment of atherosclerotic plaque itself [25]. IVWI facilitates the detection of atherosclerotic plaques. The

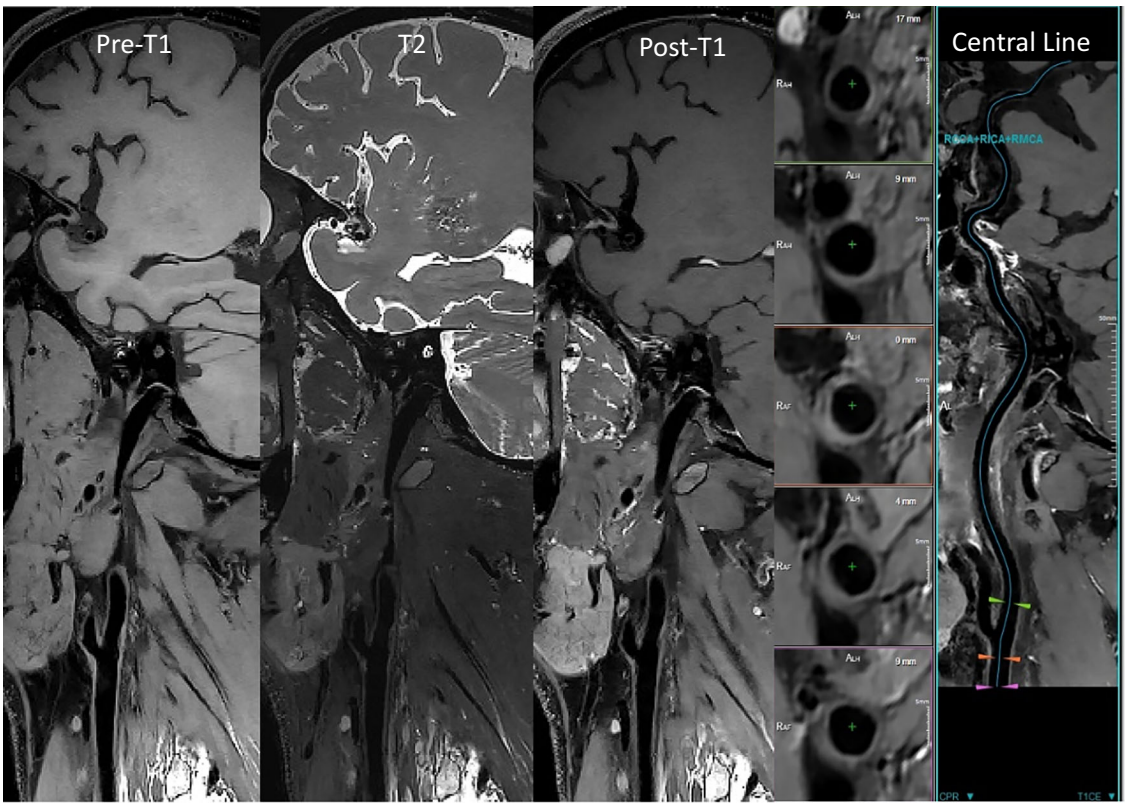

Fig. 3 Joint carotid and intracranial vessel wall imaging and automatic central line analysis

Table 2 Three levels of recommendations of iVWI for clinical practice

Indications in which iVWI is likely useful	To identify symptomatic, nonstenotic disease of the intracranial arteries
	To differentiate causes of intracranial arterial narrowing: intracranial atherosclerotic plaque, arterial dissection, vasculitis, reversible cerebral vasoconstriction syndrome, etc
	To assess the degree of stenosis and aneurysm size with improved accuracy compared to luminal imaging
Indications in which iVWI is possibly useful	To assess atherosclerotic plaque activity/vulnerability
	To assess the risk of stroke recurrence
	To determine which aneurysm has ruptured in patients with acute subarachnoid hemorrhage and multiple aneurysms
	To evaluate the instability of unruptured intracranial aneurysms
Indications in which iVWI is currently in the domain of research	To monitor the response to medical therapy of intracranial atherosclerosis or aneurysm
	To evaluate the risk of future strokes in patients with vascular risk factors
	Risk stratification of moyamoya disease
	To evaluate post-intervention vessel changes and depict the treated aneurysm during follow-up

These levels of recommendation reflect the consensus opinion of SMRA experts, based on available evidence and clinical experience

reported prevalence of < 50% stenotic culprit plaque based on MRA due to positive arterial wall remodeling is as high as 51.2% among patients with acute/subacute ischemic stroke [26]. A study including 243 patients with embolic stroke of undetermined source (ESUS) reported the prevalence of ipsilateral intracranial plaque was much higher than the contralateral side (63.8% vs 42.8%; odds ratio [OR]: 5.25; 95% confidence interval [CI]: 2.83–9.73), suggesting the etiologic role of high-risk nonstenotic intracranial plaque in ESUS [27]. 7-T MRI with higher

resolution has been reported to further facilitate the identification of underlying intracranial atherosclerosis in stroke patients who would otherwise be classified as cryptogenic, with the detection of nonstenotic (< 50%) plaque [28].

The previous consensus mentioned that iVWI showed that intracranial plaques were more common in the location opposite the origins of the branches, but those arising close to ostia were associated with infarction [1]. Multiple studies have confirmed these findings [29–31]. With improved spatial resolution and better visualization of the small perforators, 7-T iVWI also verified that plaques adjacent to the lenticulostriate artery origin have more clinical significance [32].

To differentiate causes of intracranial arterial narrowing: intracranial atherosclerotic plaque, arterial dissection, vasculitis, and reversible cerebral vasoconstriction syndrome (RCVS)

IVWI has been used to differentiate causes of arterial narrowing and help identify the etiology of acute or subacute strokes. The survey by the ASNR revealed that vasculopathy differentiation (94.4%) and cryptogenic stroke evaluation (41.3%) were its top two most common indications in clinical practice [2]. The most common appearance of intracranial atherosclerosis is eccentric wall thickening on iVWI, with a variable degree of post-contrast enhancement (Figs. 1 and 4). A comprehensive description of the vessel wall features of different vasculopathies is shown in Supplemental Table 2. Knowledge of other vasculopathy diagnoses includes:

Arterial dissection

Intracranial arterial dissection is an important cause of ischemic stroke commonly seen in younger patients [33]. Typical findings on iVWI including the presence of double lumen (a true and a false lumen), intimal flap (a curvilinear and iso/hyperintense line crossing the flow void lumen or between a hyperintense hematoma that extends to the sidewall), intramural hematoma (crescent-shaped thickening of the arterial wall that is isointense/hyperintense on pre-contrast T1-weighted images), irregular surface (a discontinuity of the juxtaluminal surface of the intramural hematoma), and intraluminal thrombus (a hyperintense filling within the lumen on pre-contrast images) [34]. An example is shown in the Supplemental Figure. IVWI was reported with improved resolution, and the black blood technique enables a higher detection rate than MRA for intramural hematoma and intimal flap, which aids the diagnosis [35, 36]. In studies including patients with cervicocranial arterial dissection, the presence of irregular surface and intraluminal thrombus was independently associated with acute ischemic stroke [34], and intraluminal thrombus was independently associated with stroke occurrence [37].

Vasculitis

Vessel wall inflammation leads to varying degrees of arterial stenosis and beading, which could be non-specific on luminal imaging such as MRA and requires further differential diagnosis. IVWI could reveal the inflammation-induced changes of the vessel wall itself, which typically present as smooth, homogeneous, concentric arterial wall thickening and enhancement. However, eccentric wall enhancement has also

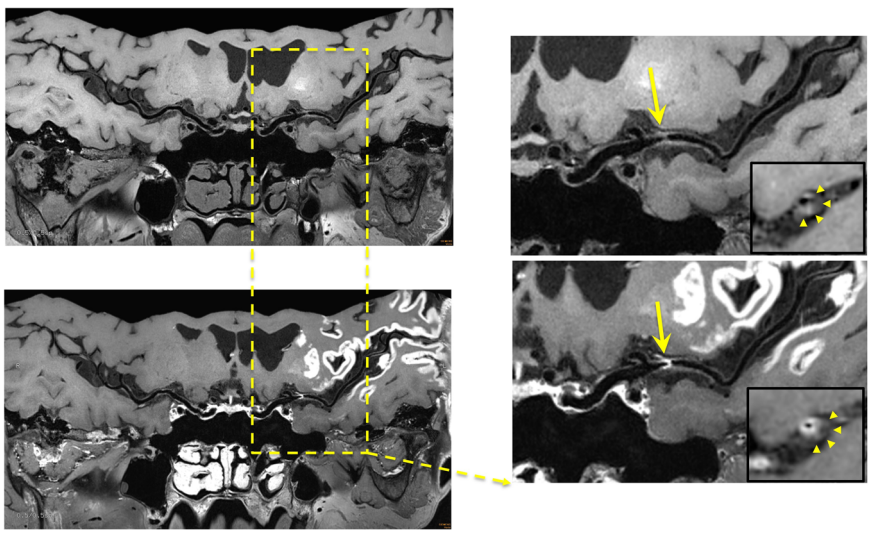

Fig. 4 An approx. 60-year-old patient with a left middle cerebral artery atherosclerotic plaque. Eccentric wall thickening (arrows) was present on pre-contrast images (top row). Strong enhancement (arrows) was shown on the post-contrast images (bottom row). The enhancement was only present on the plaque-lumen boundary rather than the entire plaque (arrowheads in the zoomed-in cross-sectional images)

been reported, possibly due to the enhancement of extending vasa vasorum, requiring careful interpretation [38]. Studies suggest a decrease or resolution of vessel wall enhancement after treatment. However, more studies are needed to understand the imaging resolution time course for follow-up plans. Interestingly, infectious vs inflammatory vasculitides may have different imaging resolution time courses. One systematic review showed that patients with VZV/HSV vasculitis more frequently showed a decrease or full resolution of vessel wall enhancement after therapy compared to primary angiitis of the central nervous system [39].

RCVS

The occurrence of RCVS may be related to transient cerebral vascular dystonia, leading to multifocal arterial constriction and dilation. Typical findings on iVWI of RCVS are multi-segmental or diffuse wall thickening of intracranial arteries, with or without minimal enhancement, which can resolve completely after 3 months of follow-up [38]. While both RCVS and vasculitides show vessel wall thickening, RCVS typically shows no or mild enhancement, concordant with the limited histopathologic data in RCVS showing an absence of vessel wall inflammation [40]. Patients are treated symptomatically and typically have a good prognosis. Because vasculitis is treated with steroids or immunosuppressants, expedient diagnosis is important, and iVWI may facilitate early differentiation between vasculitis and RCVS.

To assess the degree of stenosis and aneurysm size with better accuracy than luminal imaging

It was reported that 3D iVWI showed better agreement with digital subtraction angiography (DSA) in measuring stenosis than time-of-flight (TOF) MRA, with excellent interreader agreement in measurement. On the other hand, TOF MRA significantly overestimated the degree of stenosis, which has been attributed to signal loss caused by spin dephasing [41]. Another study demonstrated that 3D iVWI had better agreement with DSA and smaller measurement error than TOF or contrast-enhanced MRA for the size measurement of unruptured intracranial aneurysms. In particular, iVWI enabled accurate measurements of aneurysms with intraluminal thrombus compared to MRA, which tended to underestimate the aneurysm size [42]. Compared to contrast-enhanced MRA, iVWI provided comparable accuracy in stenosis evaluation as a non-contrast modality, which would be especially helpful for follow-up monitoring.

Indications in which iVWI is possibly useful

To assess atherosclerotic plaque activity/vulnerability

iVWI enables characterization of the plaques regarding the size, distribution, intrinsic T1 hyperintensity (usually interpreted as intraplaque hemorrhage), and degree of enhancement, which helps the identification of high-risk plaques that cause downstream stroke (e.g., culprit plaques, plaque with high activity/vulnerability). Due to the limitation of spatial resolution, it is difficult for current iVWI techniques to quantitatively evaluate plaque composition and features such as a lipid core or fibrous cap.

Plaque enhancement, typically defined as signal greater than normal vessel wall (grade 1) or greater than the pituitary stalk (grade 2), or quantitatively normalized as plaque-to-pituitary stalk contrast enhancement ratio, has been most extensively reported as a high-risk feature associated with plaque activity/vulnerability [43, 44]. Other frequently reported features include T1 hyperintensity defined as > 150% signal relative to muscles on pre-contrast T1-weighted images [45]; plaque burden, defined as (plaque area/vessel area) × 100% measured on the maximal stenosis site [45, 46]; and remodeling, commonly quantified by remodeling index (Outer wall area of the lesion site/outer wall area of the reference site) [47]. In addition, some atherosclerotic plaque arises close to ostia, and iVWI has revealed that middle-cerebral-artery plaques with associated infarction have more superior wall involvement than plaques without infarction [48].

To assess the risk of stroke recurrence

The plaque characteristics depicted on iVWI have also been used to predict recurrent strokes. Longitudinal studies [49–51] reported that higher plaque burden and higher enhancement ratio were significantly associated with stroke recurrence. Another study found that coexisting intracranial T1W hyperintensity and extracranial carotid atherosclerosis independently predicted stroke recurrence [52]. A recent prospective multicenter study reported that T1W hyperintensity was significantly associated with recurrent ipsilateral stroke [53]. Summarizing the emerging study results, a recent meta-analysis including 18 studies (2240 participants during an average of 16-month follow-up) concluded that plaque enhancement, plaque enhancement ratio, plaque thickness, T1W hyperintensity, and the degree of stenosis emerged as strong imaging biomarkers of stroke recurrence, indicating that iVWI has potential value in the selection of patients for aggressive treatment and improve the secondary prevention of intracranial plaques [54].

To determine which aneurysm has ruptured in patients with acute subarachnoid hemorrhage and multiple aneurysms

IVWI may be useful to determine which aneurysm has ruptured in patients with acute subarachnoid hemorrhage, particularly in the setting of angiogram-negative subarachnoid hemorrhage or multiple aneurysms [55, 56]. Blister aneurysms

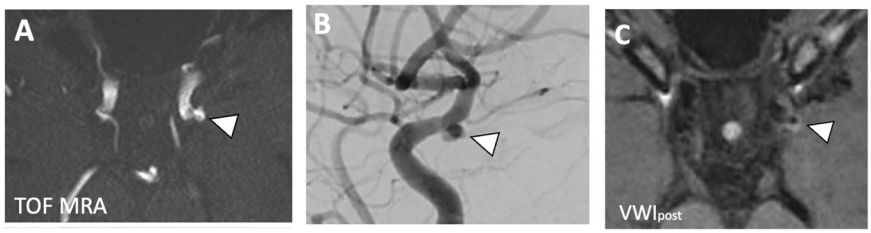

Fig. 5 An approx. 30-year-old woman with subarachnoid hemorrhage with a left internal carotid artery aneurysm. **A** TOF MRA shows the aneurysm (arrowhead). **B** A catheter cerebral angiogram confirmed the aneurysm finding (arrowhead). **C** Postcontrast vessel wall MR imaging showed a rim of aneurysmal dome enhancement on postcontrast vessel wall MR imaging (arrowhead)

or perforator aneurysms may not be apparent by CTA or DSA initially due to thrombus occluding the tiny sac; however, on iVWI, the thrombus may show enhancement, highlighting the source of hemorrhage. Moreover, when multiple aneurysms are present, the culprit ruptured aneurysm may demonstrate enhancement on iVWI, helping in direct management [57].

To evaluate the instability of unruptured intracranial aneurysms

Detecting vessel wall instability of unruptured aneurysms remains an area of active investigation. Vessel wall enhancement on iVWI has been reported to be associated with inflammatory cell invasion, neovascularization, and the presence of vasa vasorum, which could be involved in the development and subsequent rupture of cerebral aneurysms [58, 59]. An example of intracranial aneurysm wall enhancement is shown in Fig. 5. There has been a remarkable increase and accumulation of evidence since the last consensus of ASNR, showing that the enhancement of the aneurysm wall is useful for evaluating aneurysm instability and predicting future growth, which justified the upgrade of the recommendation level of this indication. Earlier studies have indicated that wall enhancement pattern (circumferential) and stronger enhancement were associated with aneurysm instability (symptomatic or changing over time) [14, 60]. A meta-analysis including 12 studies before 2021 indicated that wall enhancement on iVWI was positively associated with aneurysm rupture, growth, or symptomatic presentation with high sensitivities and mixed specificities [61]. A recent large-scale longitudinal study followed 1351 patients from 83 Chinese medical centers with unruptured intracranial aneurysms for 4 years, and found that circumferential enhancement independently predicts aneurysm growth or rupture (adjusted hazard ratio, 2.21; 95% CI: 1.56–3.13 [62]). In the subgroup of patients with circumferential enhancement, the risk of growth or rupture within 4 years was 36.8%.

Studies on fusiform aneurysms explored the 3D distribution of wall enhancement and proposed more detailed biomarkers such as averaged wall enhancement, maximal wall enhancement, and enhancement area [24].

Indications in which iVWI is currently in the domain of research

A list of emerging biomarkers of iVWI for potentially useful/research-domain indications is listed in Table 3.

To monitor the response to medical therapy of intracranial atherosclerosis or aneurysm

Hypothesis-generating studies have extended the utility of iVWI to patient-specific therapy monitoring in situ. A study including patients with symptomatic intracranial atherosclerotic plaques reported that plaque length, wall thickness, plaque burden, luminal stenosis, and plaque enhancement were significantly reduced after treatment with statins for > 6 months [63]. A randomized controlled trial in patients with intracranial aneurysms ($n = 60$) found statin use over 6 months significantly reduced wall enhancement index and volume, while the aneurysm size did not change [15]. Another study, including 127 fusiform intracranial aneurysms, showed that statin use was the only independent factor significantly associated with decreased wall enhancement ($p = 0.007$) [64].

To evaluate the risk of future strokes in patients with vascular risk factors

It was hypothesized that a presymptomatic assessment of intracranial atherosclerotic lesions is crucial to prevent a cascade of poststroke neurophysiological complications. It has been reported that intracranial atherosclerosis diagnosed by iVWI was associated with an increased long-term risk of vascular events [65–67]. More details are shown in the Supplemental material.

Risk stratification of moyamoya disease

Recent studies showed concentric wall enhancement, and that could be associated with intracranial hemorrhage [68]; wall thickening and enhancement could predict future ischemic events in patients with cerebrovascular "moyamoya" disease (showing progressive steno-occlusive changes at the terminal

Table 3 Emerging biomarkers of iVWI for possibly useful/research-domain indications

Indication	Proposed biomarkers and their utility value	Utility value
To monitor the response to medical therapy of intracranial atherosclerosis or aneurysm	Plaque length, wall thickness, plaque burden, and plaque enhancement	For symptomatic intracranial atherosclerotic plaques [65]
	Wall enhancement index and volume	For intracranial aneurysms [16]
	Wall enhancement decreases	For fusiform intracranial aneurysms [66]
To evaluate the risk of future strokes in patients with vascular risk factors	Prevalence of intracranial atherosclerotic plaque	Associated with an increased long-term risk of ischemic stroke [67]
	Plaque enhancement ratio >1.77	Predictive of risk of future stroke [68]
	Vessel wall enhancement	Predictive of acute and future stroke in cerebral amyloid angiopathy [69]
Risk stratification of Moyamoya disease	Concentric wall enhancement	Possibly associated with intracranial hemorrhage [70]
	Wall thickening and enhancement	Possibly predictive of future ischemic events [71]
To evaluate post-intervention vessel changes and depict the treated aneurysm during follow-up	For intracranial arterial stenotic diseases:	
	Vessel wall enhancement	Associated with a greater number of device passes through the occluded vessel, with hemorrhagic conversion in the infarct territory [72, 73]
	Plaque eccentricity and negative remodeling	Associated with failure of balloon angioplasty [76]
	Lower frequency of plaque eccentricity and higher enhancement ratio at baseline	Associated with in-stent restenosis [77]
	For intracranial aneurysms:	
	Vessel wall enhancement immediately after endovascular treatment of ruptured aneurysms	Associated with subsequent angiographic vasospasm [74]
	Visual evaluation	For evaluating aneurysm remnants and parent artery patency [79]

portion of the ICA associated with abnormal net-like vessels in the base of the brain) [69]. An example is shown in Fig. 6. The incidence of wall thickening and enhancement could be varied based on a different cohort of moyamoya disease, based on genetics, pathophysiological processes, iVWI techniques, and/or environmental factors. More details are discussed in the Supplemental material.

To evaluate post-intervention vessel changes and depict the treated aneurysm during follow-up

The effects of thromboembolism and mechanical thrombectomy on the arterial wall depicted by iVWI are worth investigating. Recognition of post-interventional arterial wall enhancement is important to avoid misinterpretation as preexisting primary arteriopathy [70–72]. Nevertheless, pre-treatment evaluation of plaques by iVWI has been used to predict unfavorable outcomes after intervention [73–75]. iVWI has also been employed for follow-up evaluation after intervention of intracranial aneurysm [76, 77]. More details are shown in the Supplemental material.

To summarize, a list of emerging biomarkers of iVWI for possibly useful/research-domain indications is listed in Table 3.

Pitfalls in interpretation

Generally, all MR studies are sensitive to motion artifacts, and even more so in iVWI because of the relatively long acquisition times. A study showed that about 10% of iVWI scans had motion artifacts so severe that the images could not be used for clinical diagnosis [17]. The importance of minimizing motion can be communicated to the patient prior to the scan acquisition. More effective acceleration techniques to decrease scan times are helpful, such as compressed sensing or controlled aliasing in parallel imaging (CAIPI) [11, 78]. Reliable post-scan denoising techniques can also be applied. Motion compensation using real-time tracking or retrospective motion estimation is potentially useful but still under investigation [79, 80].

More specific artifacts regarding iVWI include: (1) slow-flow artifacts, which are often more obvious in slow flow within an aneurysm (especially large aneurysms), dilated

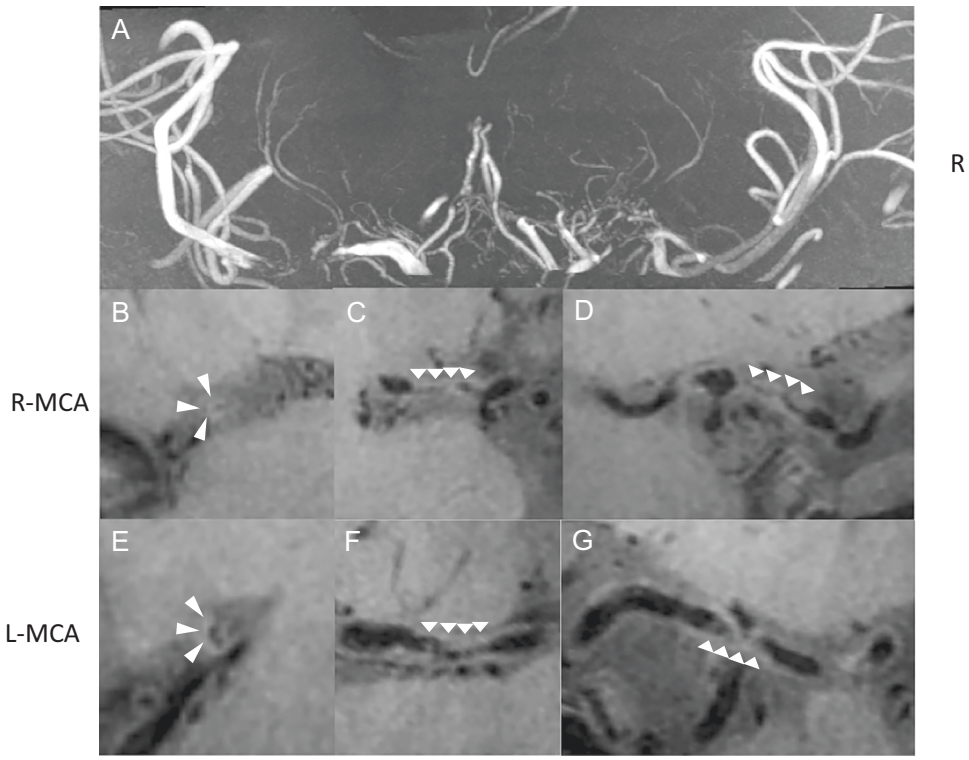

Fig. 6 An approx. a 40-year-old male who had dizziness and right limb weakness for over three years. He was diagnosed with moyamoya disease by DSA and scanned with 7-T iVWI. **A** MRA shows bilateral severe stenosis from the beginning of the middle cerebral arteries, accompanied by smoke-like small vascularity at the cranial base. **B**–**D** iVWI shows diffused wall thickening in the right middle cerebral artery, and **E**–**G** in the left middle cerebral artery. Image courtesy of Prof. Xingquan Zhao

arteries, or retrograde filling from collateral vessels [81]. MSDE and DANTE can be used to reduce slow-flow artifacts. (2) Free-induction decay artifact, which may appear as a linear dashed pattern. The vessel wall will appear similarly dashed, a "zigzag" pattern mimicking vessel wall thickening and/or a lesion [82].

In addition, there could be age-related vasa vasorum enhancement in the large intracranial arteries near the skull base. Normally, enhancing veins that are commonly seen close to arteries could mimic arterial enhancement [1]. It is strongly recommended that imaging findings be reviewed across all acquired sequences to confirm the presence of pathology, artifact, or other non-pathological entities.

Limitation

The lack of a fully rigorous consensus methodology (such as a Delphi method) is a limitation of this study.

Conclusion

IVWI techniques are now sufficient to meet the needs of many clinical uses, although blood suppression, acceleration strategies, and automatic post-processing methods can be further optimized. It is recommended to employ iVWI to identify and differentiate causes of intracranial arterial narrowing, thereby initiating etiological treatment. It has great potential in risk stratification, such as assessing plaque vulnerability, the risk of stroke recurrence, and aneurysm instability. More indications, such as monitoring post-intervention condition and the response to medical therapy, are under active research. As more evidence continues to accumulate, it is possible that a more updated consensus will be reached in the coming years.

Abbreviations

ASNR	American Society of Neuroradiology
DANTE	Delay alternating with nutation for tailored excitation
DSA	Digital subtraction angiography
iVWI	Intracranial vessel wall MR imaging
MSDE	Motion-sensitized driven-equilibrium
RCVS	Reversible cerebral vasoconstriction syndrome
SMRA	Society for Magnetic Resonance Angiography
SNR	Signal-to-noise ratio
TOF	Time-of-flight

Supplementary information

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Compliance with ethical standards

Guarantor
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Conflict of interest
The authors of this manuscript declare no relationships with any companies, whose products or services may be related to the subject matter of the article.

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Informed consent
Written informed consent was not required for this study because this is a review paper.

Only if the study is on animals
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Methodology

- Review paper

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