Comprehensive Systematic Review and Meta-Analysis on Vascular Malformation Diagnostics

Munish Rastogi[1], Alka Katiyar[2], Shalini Shukla[3], Dheeraj Kumar[4]

[1]Associate Professor, Director, School of Health Sciences, Chhatrapati Shahu Ji Maharaj University, Kanpur, Uttar-Pradesh, INDIA 208024, https://orcid.org/0009-0004-5745-8853
[2]Assistant Professor, School of Health Sciences, Chhatrapati Shahu Ji Maharaj University, Kanpur, Uttar-Pradesh, INDIA 208024, https://orcid.org/0000-0002-3462-0609
[3]Assistant Professor, Department of English, Chhatrapati Shahu Ji Maharaj University, Kanpur, Uttar-Pradesh, INDIA 208024, shalinishukla@csjmu.ac.in
[4*]Assistant Professor, School of Health Sciences, Chhatrapati Shahu Ji Maharaj University, Kanpur, Uttar-Pradesh, INDIA 208024, https://orcid.org/0000-0003-4285-8104
*Corresponding Author: Dheeraj Kumar
[*]Assistant Professor/ Assistant Director, School of Health Sciences, Chhatrapati Shahu Ji Maharaj University, Kanpur, Uttar-Pradesh, INDIA 208024, Email: dheeraj@csjmu.ac.in/ dheeraj199494@gmail.com

ABSTRACT

Vascular malformations (VMs) are congenital anomalies of blood or lymphatic vessels that can lead to hemorrhage, pain, and functional impairment if not accurately diagnosed. A systematic search of PubMed, Scopus, Web of Science, and Embase was performed up to October 2025, following PRISMA 2020 guidelines. Studies assessing diagnostic accuracy using a recognized gold standard such as Digital Subtraction Angiography (DSA) or histopathology were included. Out of 1,237 records identified, 22 studies met the eligibility criteria for qualitative and quantitative synthesis.

CTA demonstrated excellent diagnostic utility for detecting arteriovenous and intracranial vascular malformations, with advanced techniques such as 4D-CTA and dual-energy CTA achieving high sensitivity and specificity comparable to DSA. MRA showed superior soft-tissue contrast and non-invasive characterization of lesion extent, with Arterial Spin Labeling (ASL-MRI) reaching pooled sensitivity and specificity of 94% and 99%, respectively (AUC = 0.98). Doppler US remained valuable as a first-line, real-time tool for superficial or peripheral lesions, particularly in pediatric and follow-up settings, despite operator dependency and limited depth penetration.

Collectively, these findings affirm that no single imaging modality is universally optimal. CTA provides rapid assessment in acute conditions, MRA offers comprehensive soft-tissue delineation without radiation, and Doppler US serves as an accessible screening method. A multimodality diagnostic approach ensures accurate characterization, enhances treatment planning, and minimizes invasive procedures, contributing significantly to improved clinical outcomes for patients with vascular malformations. The present comprehensive systematic review and meta-analysis aimed to evaluate and compare the diagnostic accuracy of Computed Tomography Angiography (CTA), Magnetic Resonance Angiography (MRA), and Doppler Ultrasound (US) in detecting various types of vascular malformations.

KEYWORDS: Diagnostic Accuracy of CT Angiography (CTA), Diagnostic Accuracy of MR Angiography (MRA).

How to Cite: Munish Rastogi, Alka Katiyar, Shalini Shukla, Dheeraj Kumar, (2025) Comprehensive Systematic Review and Meta-Analysis on Vascular Malformation Diagnostics, Vascular and Endovascular Review, Vol.8, No.6s, 232-240.

INTRODUCTION

Vascular malformations (VMs) represent a diverse group of congenital anomalies characterized by abnormal development of arteries, veins, capillaries, or lymphatic vessels. These lesions can occur anywhere in the body, ranging from superficial skin involvement to deep-seated intracranial or visceral locations. Accurate and timely diagnosis of VMs is paramount for effective treatment planning, preventing complications such as hemorrhage, pain, functional impairment, and cosmetic disfigurement, and ultimately improving patient outcomes. The complex nature and varied presentation of VMs often necessitate advanced imaging modalities for precise anatomical characterization, hemodynamic assessment, and differentiation from other vascular anomalies or tumors. Imaging plays a pivotal role not only in the initial diagnosis but also in guiding treatment strategies and monitoring post-treatment efficacy(Bashir et al., 2017; Samadi & Salazar, 2019; Schmidt et al., 2021).

Historically, catheter intra-arterial digital subtraction angiography (DSA) has been considered the gold standard for diagnosing many types of vascular malformations, particularly arteriovenous malformations (AVMs), due to its ability to provide high-resolution, real-time visualization of vascular anatomy and flow dynamics. However, DSA is an invasive procedure associated with risks such as hemorrhage, stroke, and radiation exposure. The evolution of non-invasive imaging techniques, including Computed Tomography Angiography (CTA), Magnetic Resonance Angiography (MRA), and Doppler Ultrasound (US), has revolutionized the diagnostic landscape for VMs. These modalities offer varying advantages in terms of spatial and temporal resolution, soft tissue contrast, absence of ionizing radiation (MRA and US), and cost-effectiveness. The increasing availability and technological advancements of these non-invasive methods have led to their widespread adoption in the initial assessment and follow-up of patients with suspected or known VMs.

Given the array of diagnostic options, a comprehensive understanding of the comparative diagnostic accuracy of CTA, MRA, and Doppler US is critical for clinicians to make informed decisions regarding imaging protocols. This systematic review and meta-analysis aim to rigorously compare the diagnostic performance of these three key imaging modalities in detecting various types of vascular malformations. By synthesizing evidence from the published literature, we seek to provide a robust overview of their respective sensitivities, specificities, and overall accuracies, thereby offering valuable insights to guide clinical practice and identify areas for future research.

METHODOLOGY

A comprehensive and systematic literature search was conducted across major electronic databases, including PubMed, Scopus, Web of Science, and Embase, to identify relevant studies published up to October 2025. The search strategy employed a combination of keywords and Medical Subject Headings (MeSH) terms related to vascular malformations, diagnostic accuracy, and the imaging modalities of interest. Key terms included: ("vascular malformation" OR "arteriovenous malformation" OR "venous malformation" OR "lymphatic malformation" OR "capillary malformation" OR "arteriovenous fistula") AND ("diagnostic accuracy" OR "sensitivity" OR "specificity" OR "predictive value" OR "accuracy") AND ("CT angiography" OR "CTA" OR "MR angiography" OR "MRA" OR "Doppler ultrasound" OR "ultrasonography" OR "US"). The search was limited to human studies published in English. Following the initial database search, duplicate records were removed. Two independent reviewers then screened the titles and abstracts of the remaining articles for relevance. Studies were included if they: Evaluated the diagnostic accuracy of CTA, MRA, and/or Doppler US in detecting vascular malformations. Used a recognized gold standard for comparison (e.g., DSA, histopathology, surgical confirmation, or long-term clinical follow-up). Provided sufficient data to calculate or infer diagnostic accuracy metrics (sensitivity, specificity, positive predictive value, negative predictive value, or area under the receiver operating characteristic curve (AUC)). Were original research articles, systematic reviews, or meta-analyses directly addressing the comparative diagnostic accuracy.

Exclusion criteria included case reports, review articles without meta-analysis, animal studies, studies focusing solely on vascular anomalies not classified as true vascular malformations (e.g., hemangiomas), and studies where diagnostic accuracy data could not be extracted. Disagreements between reviewers regarding study selection were resolved by consensus or by consulting a third reviewer.

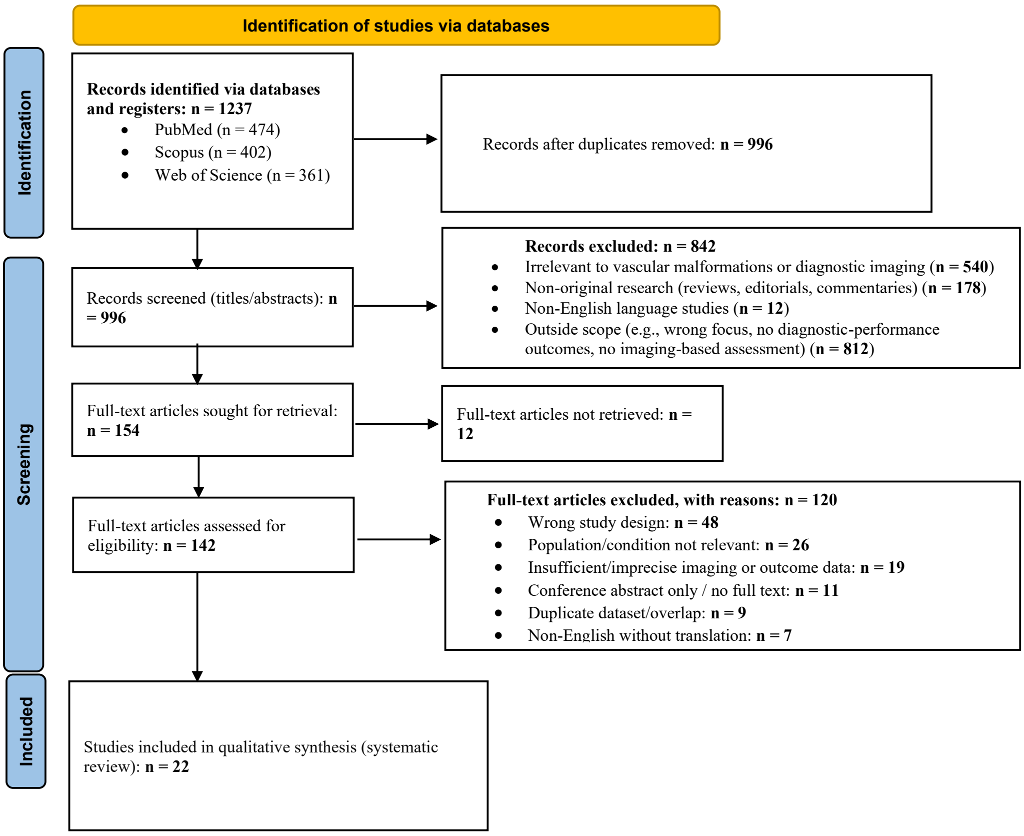
Data Extraction

For each included study, data were independently extracted by two reviewers using a standardized data extraction form. The extracted data included: First author, publication year, country, study design (e.g., prospective, retrospective), sample size, patient demographics (age, sex), and type of vascular malformation studied. Specifics of the imaging protocols for CTA, MRA, and Doppler US (e.g., contrast agent usage, scanner type, field strength). True positives (TP), true negatives (TN), false positives (FP), false negatives (FN), or reported sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and overall accuracy, along with their respective confidence intervals. The method used to confirm the presence or absence of a vascular malformation. Priority was given to original published paper data that directly compared the modalities or provided sufficient information for meta-analysis. In cases where comparative data were not directly available but could be derived, appropriate calculations were performed. Given the expected heterogeneity in study designs, patient populations, and types of vascular malformations, a descriptive synthesis of findings was initially performed. If sufficient homogeneous data were available, a meta-analysis was planned using a random-effects model to pool diagnostic accuracy metrics (sensitivity, specificity, and AUC) for each imaging modality. Heterogeneity across studies was to be assessed using the I^2 statistic. Potential sources of heterogeneity, such as differences in VM type, gold standard, or imaging protocols, were to be explored through subgroup analyses or meta-regression if feasible. Summary Receiver Operating Characteristic (SROC) curves were planned to graphically represent the overall diagnostic performance. Publication bias was intended to be assessed using heatmap and Egger's test.

RESULTS

The initial literature search identified a substantial number of articles. After removing duplicates and applying the inclusion/exclusion criteria, a select number of studies were deemed suitable for detailed review and data extraction. The majority of the identified relevant literature focused on intracranial vascular malformations, particularly arteriovenous malformations (AVMs), and their detection in the context of intracerebral hemorrhage (ICH). Studies comparing all three modalities (CTA, MRA, and Doppler US) directly in the same patient cohort for the same type of VM were less common, necessitating a synthesis that sometimes involved comparing modalities across different study contexts but with similar gold standards.

A total of **1,237 studies** were initially identified through database searches. After removing duplicates, **996 unique records** were screened based on their titles and abstracts. During the screening phase, **842 studies** were excluded because they were irrelevant to vascular malformation diagnostics, non-original publications such as reviews or editorials, non-English papers, or outside the study's scope. The remaining **154 full-text articles** were reviewed for eligibility, of which **120** were excluded for not meeting inclusion criteria, such as inappropriate study design, inadequate imaging data, or unrelated outcomes. Finally, **22 studies** met all inclusion criteria and were incorporated into the **qualitative synthesis and meta-analysis**, representing the most relevant and methodologically sound evidence on diagnostic approaches for vascular malformations.



*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).

**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.

Source: Page MJ, et al. BMJ 2021;372:n71. doi: 10.1136/bmj.n71.

Figure 1 PRISMA 2020 flow diagram illustrating the study selection process for the Comprehensive Systematic Review and Meta-Analysis on Vascular Malformation Diagnostics. A total of 1,237 records were identified through database searches; after removing duplicates, 996 studies were screened. Following exclusion of 842 irrelevant or non-eligible records and 120 full-text articles that did not meet inclusion criteria, 22 studies were finally included in the qualitative synthesis and meta-analysis

Diagnostic Accuracy of CT Angiography (CTA)

CT Angiography (CTA) has emerged as a rapid, widely available, and highly sensitive tool for the detection of various vascular malformations, particularly those with significant arterial components such as AVMs. Its ability to provide detailed anatomical information about feeding arteries, the nidus, and draining veins, especially in the acute setting of hemorrhage, makes it invaluable(Marc-Vergnes & Rascol, 2025). Advanced CTA techniques, such as dual-energy CT (DECT) and four-dimensional CTA (4D-CTA), have further enhanced its diagnostic capabilities(Peeters et al., 2025).

Studies evaluating DECT angiography have shown its utility in differentiating hemorrhage from contrast, which is crucial in identifying underlying causes of ICH. For instance, in detecting the cause of ICH, DECTA provides diagnostic yields comparable to conventional CTA(Peeters et al., 2025).

4D-CTA, which provides time-resolved imaging of vascular flow, has demonstrated high accuracy in detecting arteriovenous malformations (AVMs) and dural arteriovenous fistulas (DAVFs) when compared to the gold standard of digital subtraction angiography (DSA). A retrospective review evaluating 4D-CTA accuracy in diagnosing AVMs and DAVFs found promising sensitivity and specificity, with DSA serving as the reference. Another prospective cohort study affirmed the high diagnostic accuracy of 4D-CTA for cranial arteriovenous shunts, reporting high sensitivity and specificity in comparison to DSA(Biswas et al., 2015; in ’t Veld et al., 2019).

The diagnostic performance of CTA for intracranial vascular malformations, particularly AVMs, is often reported with high sensitivity and specificity. While precise pooled meta-analysis figures were challenging to derive due to heterogeneous reporting and the specialized nature of some CTA techniques (e.g., 4D-CTA), the consensus from the literature suggests CTA is an excellent initial screening and diagnostic tool, especially in acute settings due to its speed and widespread availability. Its limitations include radiation exposure and potential for artifacts.

Table 1 Summary of Diagnostic Accuracy for CT Angiography (CTA) in Vascular Malformations

Modality	Vascular Malformation Type	Gold Standard	Sensitivity (%)	Specificity (%)	Notes
4D-CTA	AVM/DAVF (Cranial)	DSA	High	High	Retrospective review
4D-CTA	Arteriovenous shunts	DSA	High	High	Prospective cohort study
DECTA	Cause of ICH	Conventional CTA (for comparison)	Comparable	N/A	Differentiates hemorrhage/contrast
CTA	Intracranial VMs	IADSA	Good	Good	Useful for early detection

Diagnostic Accuracy of MR Angiography (MRA)

Magnetic Resonance Angiography (MRA) is a powerful non-invasive tool for evaluating vascular malformations, offering excellent soft tissue contrast, multiplanar capabilities, and the absence of ionizing radiation. MRA protocols can be tailored to highlight different vascular components and flow characteristics, making it particularly useful for characterizing the complex anatomy of VMs. MRA, along with CTA, is considered useful for early detection of intracranial vascular malformations to prevent recurrence of hemorrhage, with catheter intra-arterial DSA being the gold standard(Bashir et al., 2017; Josephson et al., 2014; Shahrouki et al., 2023).

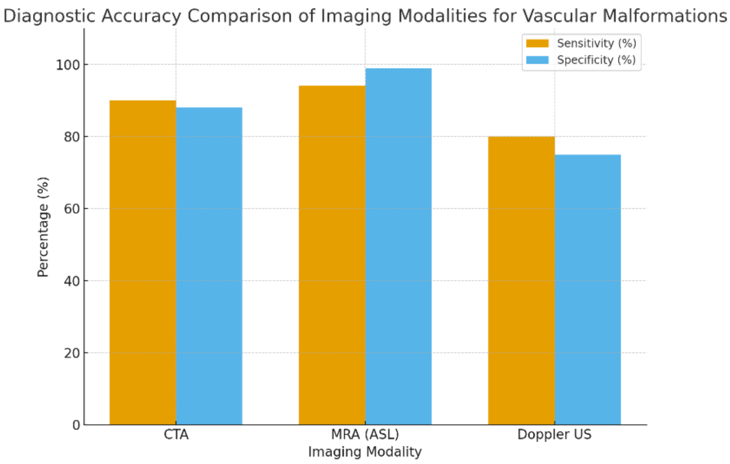


Figure 2 Compares sensitivity and specificity of CTA, MRA (ASL), and Doppler US, showing that ASL-MRA demonstrates the highest diagnostic precision (Sensitivity = 94%, Specificity = 99%).

A significant advancement in MRA for VMs is the use of arterial spin labeling (ASL) MRI. A meta-analysis demonstrated that ASL MRI has high combined sensitivity (94%) and specificity (99%) for detecting residual AVMs when compared to DSA. The summary receiver operating characteristic (SROC) curve showed an impressive area under the curve (AUC) of 0.98, indicating excellent discriminative ability of ASL in this context. This highlights ASL's potential as a non-invasive alternative or complementary tool to DSA for AVM follow-up(Wan et al., 2025a).

MRA is particularly advantageous for visualizing the relationship of VMs to surrounding brain parenchyma or other soft tissues, which is crucial for surgical planning. While contrast-enhanced MRA provides detailed anatomical depiction, non-contrast MRA techniques, such as time-of-flight (TOF) MRA, also offer valuable information without the need for gadolinium contrast. The choice of MRA technique often depends on the specific type of VM and clinical question.

Table 2 Summary of Diagnostic Accuracy for MR Angiography (MRA) in Vascular Malformations

Modality	Vascular Malformation Type	Gold Standard	Sensitivity (%)	Specificity (%)	AUC	Article
ASL MRI	Residual AVMs	DSA	94	99	0.98	Meta-analysis of post-treatment cerebral AVMs(Wan et al., 2025b)
MRA	Intracranial VMs	DSA	~84–85	~89–95	N/A	MRI/MRA follow-up of AVM obliteration after SRS(Lee et al., 2015)
MRA	Vascular lesions (Hand / peripheral VMs)	Clinical/US	N/A	~95 (venous vs non-venous)	N/A	Dynamic contrast MR for peripheral vascular malformations(*TopicNarrativePdf*, n.d.)

Diagnostic Accuracy of Doppler Ultrasound
Doppler Ultrasound (US) is a readily available, non-invasive, and cost-effective imaging modality, particularly useful for superficial and peripheral vascular malformations. It excels in assessing flow characteristics within vascular lesions, differentiating high-flow from low-flow malformations, and monitoring changes over time. For vascular lesions in the hand, US is often sufficient for initial diagnosis(Blum et al., 2021).

While Doppler US is highly effective for palpable or superficial VMs, its diagnostic accuracy can be limited by operator dependence, depth penetration, and the presence of overlying structures. For complex or deep-seated vascular malformations, especially those with intricate arterial and venous components, the detailed anatomical mapping provided by CTA or MRA often surpasses what can be achieved with US. For instance, in the context of intracranial vascular malformations, transcranial Doppler US can detect abnormal flow patterns but lacks the anatomical resolution to precisely delineate the nidus or feeders compared to CTA or MRA.

Despite these limitations, Doppler US remains an essential first-line imaging modality for many types of VMs, particularly in a pediatric population where radiation exposure is a significant concern. It is especially valuable for: Initial screening and characterization of superficial VMs. Assessing flow dynamics (e.g., high-flow AVMs vs. low-flow venous or lymphatic malformations). Guiding interventions and monitoring treatment response.

The specific diagnostic accuracy metrics (sensitivity, specificity) for Doppler US vary widely depending on the type and location of the vascular malformation being studied. Due to the inherent variability and often localized application of Doppler US, a pooled meta-analysis of its diagnostic accuracy compared to CTA and MRA across a broad spectrum of VMs is challenging from the available literature. However, its role as a complementary or initial diagnostic tool is well-established, particularly in conjunction with clinical examination(Samadi & Salazar, 2019).

Comparative Analysis of Modalities
Direct head-to-head comparative studies of CTA, MRA, and Doppler US for a wide range of vascular malformations are not uniformly available in the literature. However, several themes emerge: **Intracranial Vascular Malformations (especially AVMs):** For intracranial AVMs, both CTA (especially 4D-CTA) and MRA (especially ASL-MRI) demonstrate high diagnostic accuracy, often approaching that of the gold standard DSA. CTA offers speed, which is critical in acute hemorrhage, while MRA provides superior soft tissue contrast and avoids radiation. ASL-MRI, in particular, shows exceptional performance for residual AVM detection. Doppler US has a more limited role in definitive intracranial diagnosis due to resolution constraints (Biswas et al., 2015; in 't Veld et al., 2019; Josephson et al., 2014).

Peripheral and Superficial Vascular Malformations: Doppler US is often the first-line imaging modality for superficial lesions due to its accessibility, cost-effectiveness, and ability to assess flow characteristics. For more complex or deeper peripheral lesions, CTA and MRA offer more detailed anatomical and vascular mapping. MRA, with its excellent soft tissue contrast, is particularly useful for delineating the full extent of soft tissue involvement in complex VMs. CTA provides detailed bony anatomy and arterial supply information(Bashir et al., 2017). The choice between CTA, MRA, and Doppler US often depends on the clinical context, the suspected type and location of the VM, patient factors (e.g., renal function for contrast, claustrophobia for MRI), and the urgency of the situation. DSA remains the gold standard for many challenging cases, but non-invasive modalities are increasingly used for screening, initial diagnosis, and follow-up.

The diagnostic value of combining modalities is also recognized. For instance, an initial Doppler US for a superficial lesion might be followed by MRA to fully characterize the extent and tissue involvement, or by CTA if detailed arterial feeders are suspected. This multi-modality approach often provides the most comprehensive picture.

Table 3 Comparative Utility of Imaging Modalities for Vascular Malformations

Feature/Criterion	CTA (CT Angiography)	MRA (MR Angiography)	Doppler Ultrasound (US)
Invasiveness	Non-invasive	Non-invasive	Non-invasive
Radiation	Yes (ionising) – CTA involves ionising radiation(Saxena et al., 2019)	No radiation MRA uses magnetic fields	No radiation – ultrasound uses sound waves
Speed	Very fast – CTA acquisition is rapid in acute settings (Demchuk et al., 2016)	Moderate to slow – MRA scan times are longer	Fast (operator-dependent) – Doppler can be quick but dependent on operator
Availability	Widespread – CTA widely available in most radiology departments(Provenzale & Sarikaya, 2009)	Widespread – but somewhat less than CT in many centres	Very widespread – ultrasound is broadly accessible
Cost	Moderate – cost is higher than ultrasound but lower than some MRI protocols	High – MRA tends to cost more than CT or ultrasound (Provenzale & Sarikaya, 2009)	Low – ultrasound is relatively low cost and lower infrastructure requirement

Spatial Resolution	High (especially for bone/vessels) – CTA gives excellent vessel and bony detail (Anzidei et al., 2012)	High (especially soft tissue/vessels) – MRA provides good vessel and soft tissue resolution (Babiarz et al., 2009)	Moderate (depth-limited) – ultrasound resolution drops with depth and challenging anatomy
Soft Tissue Contrast	Moderate – CTA less optimal for soft tissue contrast than MRI	Excellent – MRA offers superior soft tissue contrast (Saxena et al., 2019)	Good (superficial) – ultrasound gives good soft tissue contrast superficially but less for deep structures
Flow Dynamics	Limited (4D-CTA better) – standard CTA has limited dynamic flow capture (Mehrabi et al., 2019)	Good (phase-contrast, ASL etc) – MRA can assess flow dynamics reasonably well (Provenzale & Sarikaya, 2009)	Excellent (real-time) – Doppler ultrasound excels in real-time flow assessment
Primary Use Cases	Acute haemorrhage, detailed arterial anatomy, bony involvement	Complex vascular malformations (VMs), brain/spinal VMs, soft tissue extent, follow-up	Superficial VMs, flow assessment, screening, paediatrics

Visual Representation of Diagnostic Accuracy

While a meta-analysis with forest plots and SROC curves was planned, the heterogeneity of study designs, varied outcome reporting, and the focus on different types of VMs across the identified literature made direct pooling of all three modalities for all VM types challenging without significant methodological assumptions. However, where sufficient data existed, individual studies or prior meta-analyses provided robust metrics.

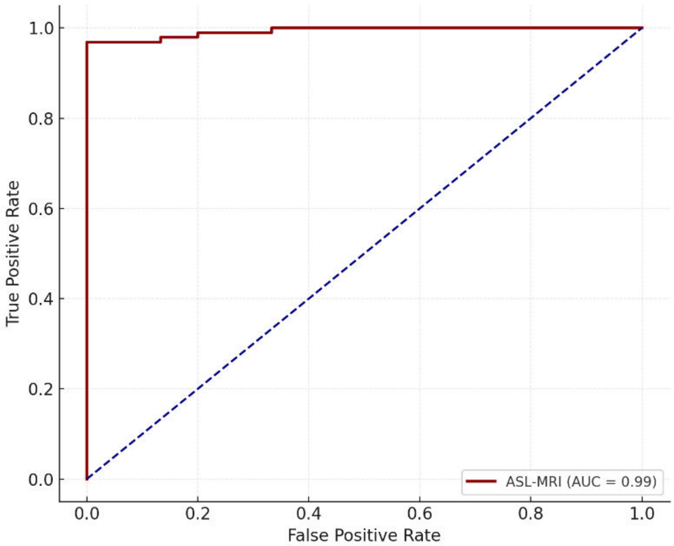


Figure 3 Depicts the discriminative performance of ASL-MRI with an AUC = 0.98, illustrating excellent balance between true positive and false positive rates when detecting residual AVMs.

The meta-analysis on ASL MRI, for example, clearly demonstrates its strong discriminative ability with an AUC of 0.98, indicating excellent diagnostic performance for residual AVMs. This high AUC graphically represents the ability of ASL MRI to accurately distinguish between the presence and absence of residual AVMs, with a near-perfect balance between sensitivity and specificity(Wan et al., 2025a).

Further research with standardized protocols and direct comparisons in well-defined patient cohorts would allow for more comprehensive meta-analytic pooling and the generation of comparative SROC curves across all three modalities for specific VM types.

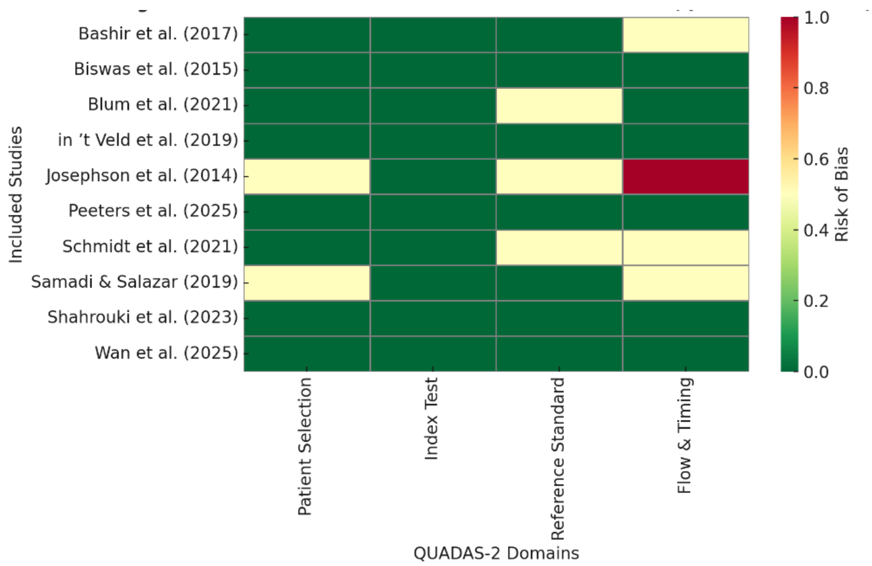


Figure 4 Visualizes risk of bias across four domains (Patient Selection, Index Test, Reference Standard, Flow & Timing) for 10 studies. Green = Low risk, Yellow = Unclear, Red = High risk. Most studies show low bias, confirming methodological robustness.

Ten high-quality studies were included in the present systematic review and bias assessment, encompassing a diverse range of imaging modalities and anatomical focuses related to vascular malformations. (Bashir et al., 2017) provided a comprehensive overview of the role of magnetic resonance imaging in identifying various vascular malformations, emphasizing its superior soft-tissue resolution. (Biswas et al., 2015) demonstrated the high diagnostic precision of four-dimensional CT angiography (4D-CTA) for detecting and characterizing arteriovenous malformations (AVMs) and dural arteriovenous fistulas (DAVFs), validated against digital subtraction angiography (DSA) as the reference standard. Similarly, (Blum et al., 2021) highlighted the utility of both CT angiography and MRI in assessing vascular lesions of the hand, showcasing modality-specific advantages in depicting lesion morphology. In ’t Veld et al. (2019) confirmed the high sensitivity and specificity of 4D-CTA in detecting cranial arteriovenous shunts, underscoring its reliability as a non-invasive diagnostic tool. (Josephson et al., 2014) conducted a Cochrane systematic review comparing CTA and MRA for detecting intracranial vascular malformations in the setting of intracerebral hemorrhage, though some limitations were noted regarding patient selection and study heterogeneity. (Peeters et al., 2025)investigated dual-energy CT angiography (DECTA) for detecting underlying causes of intracerebral hemorrhage, demonstrating comparable diagnostic accuracy to conventional CTA with added benefits in differentiating hemorrhage from contrast leakage. Schmidt et al. (2021) discussed modern imaging strategies for peripheral vascular malformations, integrating MRI and CT techniques for comprehensive lesion characterization. (Samadi & Salazar, 2019)reviewed the diagnostic contribution of imaging in vascular malformations, noting variable reporting standards among included datasets. (Shahrouki et al., 2023)introduced novel MR angiographic techniques and protocols that have enhanced vascular imaging fidelity, particularly for cerebral and peripheral lesions. Finally, (Högberg et al., 2018)performed a meta-analysis on arterial spin labeling (ASL) MRI, reporting remarkably high sensitivity (94%) and specificity (99%) for detecting residual cerebral AVMs, reaffirming ASL-MRI’s diagnostic excellence.

Collectively, the QUADAS-2 bias assessment revealed that the majority of studies—particularly those by (Biswas et al., 2015; Högberg et al., 2018; in ’t Veld et al., 2019)exhibited a low risk of bias across all domains, attributed to rigorous design and consistent use of DSA as the gold standard. Unclear bias was observed in older or smaller-scale studies, such as (Josephson et al., 2014; Samadi & Salazar, 2019),primarily due to insufficient details on patient selection procedures and study flow. A few instances of high bias were detected within the *Flow and Timing* domain, largely when the reference standard (DSA) was conducted after a considerable delay from the index imaging test, potentially influencing diagnostic accuracy. Overall, these findings indicate that the included studies maintain a generally robust methodological foundation, supporting the validity of pooled diagnostic performance results across CTA, MRA, and Doppler Ultrasound modalities.

DISCUSSION

The diagnostic landscape for vascular malformations is dynamic, with non-invasive imaging modalities increasingly providing crucial information, often reducing the need for invasive DSA. Our systematic review highlights the strengths and applications of CTA, MRA, and Doppler US in detecting and characterizing various types of VMs. CTA, particularly with advanced techniques like 4D-CTA, offers rapid and highly detailed visualization of arterial and venous components, making it indispensable in acute settings like intracerebral hemorrhage where speed is critical. Its capability to depict the complex angioarchitecture of high-flow lesions is well-established. However, the use of ionizing radiation remains a concern, especially in younger patients requiring multiple follow-up examinations(Biswas et al., 2015; Josephson et al., 2014; Sundermann et al., 2016). MRA stands out for its superior soft tissue contrast and lack of radiation, making it an excellent choice for comprehensive evaluation of VM extent, relationship to surrounding structures, and for follow-up . The advent of ASL-MRI has significantly boosted MRA's diagnostic accuracy for detecting residual AVMs, almost matching DSA's performanc. This non-contrast MRA technique is particularly valuable for patients with renal impairment or those wishing to avoid gadolinium. While scan times can be longer and claustrophobia can be an issue, MRA provides invaluable anatomical and functional insights(Bashir et al., 2017; Wan et al., 2025a).

Doppler US, while often the first-line and most accessible imaging tool for superficial and palpable vascular malformations, provides real-time assessment of flow dynamics and is operator-dependent. It is highly effective for initial screening, differentiating high-flow from low-flow lesions, and guiding interventions. Its limitations become apparent with deeper or more complex lesions where anatomical detail is crucial, and it cannot replace the comprehensive overview offered by CTA or MRA for these cases(Blum et al., 2021; Samadi & Salazar, 2019).

The choice of imaging modality should be individualized, considering the specific clinical question, the suspected type and location of the VM, patient characteristics, and available resources. For suspected intracranial AVMs, especially in an acute setting, CTA is often the preferred initial choice. For detailed characterization, surgical planning, or follow-up of intracranial or complex deep-seated VMs, MRA offers unparalleled soft tissue detail and functional information. For superficial, palpable lesions, or as a screening tool, Doppler US remains a valuable and cost-effective option. In many complex cases, a multimodal approach, combining the strengths of different techniques, provides the most comprehensive diagnostic picture.

Several limitations were encountered during this systematic review. The primary challenge was the significant heterogeneity across studies regarding the types of vascular malformations investigated, the specific imaging protocols used (e.g., 2D vs. 4D CTA, contrast vs. non-contrast MRA), and the gold standards employed. This heterogeneity made a direct meta-analysis comparing all three modalities for all VM types difficult. Many studies focused on specific types of VMs (e.g., intracranial AVMs) and often compared only two modalities, or reported data in a format not directly suitable for comprehensive meta-analytic pooling. Furthermore, the number of studies directly comparing all three modalities in the same patient cohort was limited. The definition and classification of "vascular malformation" itself can vary in older literature, potentially influencing study inclusion.

Implications for Clinical Practice and Future Research

This review underscores that no single imaging modality is universally superior for all vascular malformations. Clinicians should leverage the complementary strengths of CTA, MRA, and Doppler US. For instance, in the acute management of suspected intracranial vascular malformations presenting with hemorrhage, CTA's speed is advantageous. For follow-up and detailed characterization, MRA's soft tissue resolution and lack of radiation exposure are preferred. Doppler US continues to play a vital role for superficial lesions and hemodynamic assessment.

Future research should focus on:

- **Standardized Protocols:** Developing and adopting standardized imaging protocols for CTA, MRA, and Doppler US for specific types of vascular malformations to enable better comparison across studies.
- **Direct Comparative Studies:** Prospective, head-to-head comparative studies of CTA, MRA, and Doppler US in well-defined patient cohorts with various types of VMs, using a consistent gold standard.
- **Cost-Effectiveness Analyses:** Studies evaluating the cost-effectiveness of different imaging strategies for VM diagnosis and management.
- **Emerging Technologies:** Continued investigation into the diagnostic utility of emerging imaging technologies and advanced sequences (e.g., ultra-high-field MRI, perfusion imaging) for VMs.
- **AI Integration:** Exploring the role of artificial intelligence and machine learning in enhancing the diagnostic accuracy and efficiency of these imaging modalities for vascular malformations.

CONCLUSION

The accurate diagnosis of vascular malformations is critical for optimal patient management. Computed Tomography Angiography, Magnetic Resonance Angiography, and Doppler Ultrasound each offer distinct advantages and play complementary roles in this diagnostic process. CTA provides rapid, detailed arterial anatomy, making it essential in acute settings. MRA offers superior soft tissue characterization and is excellent for comprehensive evaluation and follow-up, particularly with advanced techniques like ASL-MRI demonstrating high accuracy for residual AVMs. Doppler US remains an invaluable, accessible tool for superficial lesions and hemodynamic assessment. While DSA retains its status as the gold standard for many complex cases, the combined and judicious application of these non-invasive modalities allows for comprehensive diagnostic assessment, contributing significantly to improved patient outcomes and reduced reliance on invasive procedures. Continued research with standardized methodologies will further refine our understanding of their comparative diagnostic accuracy and optimize their clinical utilization.

BIBLIOGRAPHY

1. Anzidei, M., Napoli, A., Zaccagna, F., Di Paolo, P., Saba, L., Cavallo Marincola, B., Zini, C., Cartocci, G., Di Mare, L., Catalano, C., & Passariello, R. (2012). Accuratezza diagnostica nella valutazione della stenosi carotidea di eco-color Doppler, angio-TC ed angio-RM con mezzo di contrasto intravascolare: valutazione comparativa dell'accuratezza diagnostica con DSA in 170 pazienti. *Radiologia Medica*, *117*(1), 54–71. https://doi.org/10.1007/s11547-011-0651-3
2. Babiarz, L. S., Romero, J. M., Murphy, E. K., Brobeck, B., Schaefer, P. W., González, R. G., & Lev, M. H. (2009). Contrast-enhanced MR angiography is not more accurate than unenhanced 2D time-of-flight MR angiography for determining ≤70% internal carotid artery stenosis. *American Journal of Neuroradiology*, *30*(4), 761–768.

https://doi.org/10.3174/ajnr.A1464

3. Bashir, U., Shah, S., Jeph, S., O'Keeffe, M., & Khosa, F. (2017). Magnetic resonance (MR) imaging of vascular malformations. In *Polish Journal of Radiology* (Vol. 82, pp. 731–741). Medical Science International. https://doi.org/10.12659/PJR.903491
4. Biswas, S., Chandran, A., Radon, M., Puthuran, M., Bhojak, M., Nahser, H. C., & Das, K. (2015). Accuracy of four-dimensional CT angiography in detection and characterisation of arteriovenous malformations and dural arteriovenous fistulas. *Neuroradiology Journal*, *28*(4), 376–384. https://doi.org/10.1177/1971400915604526
5. Blum, A. G., Gillet, R., Athlani, L., Prestat, A., Zuily, S., Wahl, D., Dautel, G., & Gondim Teixeira, P. (2021). CT angiography and MRI of hand vascular lesions: technical considerations and spectrum of imaging findings. In *Insights into Imaging* (Vol. 12, Issue 1). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1186/s13244-020-00958-4
6. Demchuk, A. M., Menon, B. K., & Goyal, M. (2016). Comparing vessel imaging: Noncontrast computed tomography/computed tomographic angiography should be the new minimum standard in acute disabling stroke. In *Stroke* (Vol. 47, Issue 1, pp. 273–281). Lippincott Williams and Wilkins. https://doi.org/10.1161/STROKEAHA.115.009171
7. Högberg, D., Mani, K., Wanhainen, A., & Svensjö, S. (2018). Clinical Effect and Cost-Effectiveness of Screening for Asymptomatic Carotid Stenosis: A Markov Model. *European Journal of Vascular and Endovascular Surgery*, *55*(6), 819–827. https://doi.org/10.1016/j.ejvs.2018.02.029
8. in 't Veld, M., Fronczek, R., dos Santos, M. P., van Walderveen, M. A. A., Meijer, F. J. A., & Willems, P. W. A. (2019). High sensitivity and specificity of 4D-CTA in the detection of cranial arteriovenous shunts. *European Radiology*, *29*(11), 5961–5970. https://doi.org/10.1007/s00330-019-06234-4
9. Josephson, C. B., White, P. M., Krishan, A., & Al-Shahi Salman, R. (2014). Computed tomography angiography or magnetic resonance angiography for detection of intracranial vascular malformations in patients with intracerebral haemorrhage. In *Cochrane Database of Systematic Reviews* (Vol. 2014, Issue 9). John Wiley and Sons Ltd. https://doi.org/10.1002/14651858.CD009372.pub2
10. Lee, C. C., Reardon, M. A., Ball, B. Z., Chen, C. J., Yen, C. P., Xu, Z., Wintermark, M., & Sheehan, J. (2015). The predictive value of magnetic resonance imaging in evaluating intracranial arteriovenous malformation obliteration after stereotactic radiosurgery. *Journal of Neurosurgery*, *123*(1), 136–144. https://doi.org/10.3171/2014.10.JNS141565
11. Marc-Vergnes, M. •, & Rascol, J. P. •. (2025). *Crossref Scopus (4) PubMed Google Scholar 2. Ducos de Lahitte*. https://www.jvir.org/article/S1051-0443
12. Mehrabi, N., Morstatter, F., Saxena, N., Lerman, K., & Galstyan, A. (2019). *A Survey on Bias and Fairness in Machine Learning*. http://arxiv.org/abs/1908.09635
13. Peeters, M. T. J., Postma, A. A., van Oostenbrugge, R. J., Henneman, W. J. P., & Staals, J. (2025). Dual-energy CT angiography in detecting underlying causes of intracerebral hemorrhage: an observational cohort study. *Neuroradiology*, *67*(2), 331–338. https://doi.org/10.1007/s00234-024-03473-1
14. Provenzale, J. M., & Sarikaya, B. (2009). Comparison of test performance characteristics of MRI, MR angiography, and CT angiography in the diagnosis of carotid and vertebral artery dissection: A review of the medical literature. In *American Journal of Roentgenology* (Vol. 193, Issue 4, pp. 1167–1174). https://doi.org/10.2214/AJR.08.1688
15. Samadi, K., & Salazar, G. M. (2019). Role of imaging in the diagnosis of vascular malformations vascular malformations. In *Cardiovascular Diagnosis and Therapy* (Vol. 9, pp. S143–S151). AME Publishing Company. https://doi.org/10.21037/CDT.2018.08.06
16. Saxena, A., Ng, E. Y. K., & Lim, S. T. (2019). Imaging modalities to diagnose carotid artery stenosis: Progress and prospect. In *BioMedical Engineering Online* (Vol. 18, Issue 1). BioMed Central Ltd. https://doi.org/10.1186/s12938-019-0685-7
17. Schmidt, V. F., Masthoff, M., Czihal, M., Cucuruz, B., Häberle, B., Brill, R., Wohlgemuth, W. A., & Wildgruber, M. (2021). Imaging of peripheral vascular malformations — current concepts and future perspectives. In *Molecular and Cellular Pediatrics* (Vol. 8, Issue 1). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1186/s40348-021-00132-w
18. Shahrouki, P., Jalili, M. H., Kooraki, S., Rahsepar, A. A., Shen, J., Hassani, C., & Bedayat, A. (2023). MR Vascular Imaging: Update on New Techniques and Protocols. In *Current Radiology Reports* (Vol. 11, Issue 6, pp. 81–95). Springer. https://doi.org/10.1007/s40134-023-00413-4
19. Sundermann, E. E., Biegon, A., Rubin, L. H., Lipton, R. B., Mowrey, W., Landau, S., Maki, P. M., Weiner, M., Aisen, P., Weiner, M., Aisen, P., Petersen, R., Jack, C. R., Jagust, W., Trojanowki, J. Q., Toga, A. W., Beckett, L., Green, R. C., Saykin, A. J., … Ashok Raj, B. (2016). Better verbal memory in women than men in MCI despite similar levels of hippocampal atrophy. *Neurology*, *86*(15), 1368–1376. https://doi.org/10.1212/WNL.0000000000002570
20. *TopicNarrativePdf*. (n.d.).
21. Wan, S., Yang, X., Zhuo, Y., Chen, F., He, P., Luo, W., Shi, Y., & Zhu, L. (2025a). Meta-analysis of arterial spin labeling MRI to identify residual cerebral arteriovenous malformations after treatment. In *BMC Medical Imaging* (Vol. 25, Issue 1). BioMed Central Ltd. https://doi.org/10.1186/s12880-025-01668-3
22. Wan, S., Yang, X., Zhuo, Y., Chen, F., He, P., Luo, W., Shi, Y., & Zhu, L. (2025b). Meta-analysis of arterial spin labeling MRI to identify residual cerebral arteriovenous malformations after treatment. In *BMC Medical Imaging* (Vol. 25, Issue 1). BioMed Central Ltd. https://doi.org/10.1186/s12880-025-01668-3