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SYSTEMATIC REVIEW

A comparison of arterial spin labelling with catheter angiography in evaluating arteriovenous malformations: a systematic review

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Objectives: To compare the performance of arterial spin labelling (ASL) in evaluating arteriovenous malformations (AVMs) against the current gold standard of catheter angiography.

Methods: We systematically reviewed the published literature using EMBASE and Medline. We included studies that compared ASL to catheter angiography in the assessment of AVMs in three outcome domains: detection, angioarchitectural and haemodynamic features.

Results: From 314 unique citations, 19 studies representing 289 patients with intracranial AVMs met our inclusion criteria. We did not pool data due to marked heterogeneity in study outcome measures. Seven studies showed high diagnostic performance of ASL in identifying arterial feeders, with sensitivity ranging from 84.6 to 100% and specificity ranging from 93.3 to 100%. Six studies showed strong ability in detecting arteriovenous

shunting, with sensitivity ranging from 91.7 to 100% and specificity ranging from 90 to 100%. Seven studies demonstrated that ASL could identify nidus location and size as well as catheter angiography, while five studies showed relatively poorer performance in delineating venous drainage. Two studies showed 100% sensitivity of ASL in the identification of residual or obliterated AVMs following stereotactic radiosurgery.

Conclusions: Despite limitations in the current evidence base and technical challenges, this review suggests that ASL has a promising role in the work-up and post-treatment follow-up of AVMs. Larger scale prospective studies assessing the diagnostic performance of ASL are warranted.

Advances in knowledge: ASL demonstrates overall validity in the evaluation of intracranial AVMs.

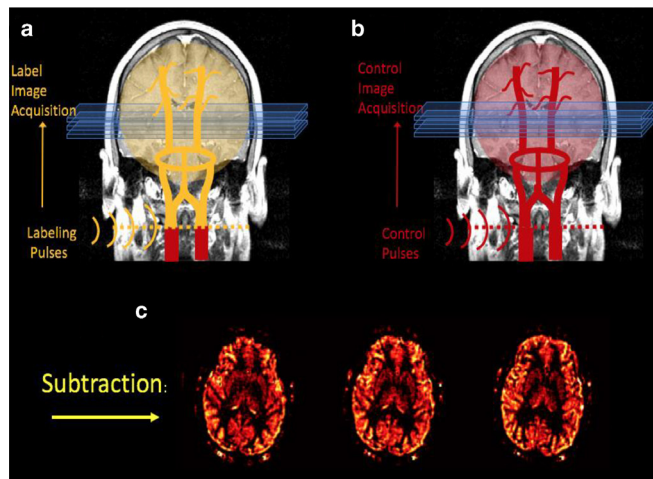
INTRODUCTION

According to the International Society for the Study of Vascular Anomalies classification, arteriovenous malformations (AVMs) are high-flow, typically congenital lesions where there is an abnormal connection between feeding arteries and draining veins without an intervening capillary bed.¹ The result is that blood is shunted through a collection of dysmorphic vessels referred to as the nidus.^{1,2} AVMs are rare and occur most frequently within the central nervous system, with an estimated incidence of approximately 1 per 100,000 per year in unselected populations.^{3,4} Other sites include the trunk and the peripheries.

There are four primary treatment options for AVMs: conservative management, surgery, endovascular embolisation or radiosurgery.⁵ Each has its own advantages and disadvantages, and the decision regarding which option

to pursue is often decided based on patient characteristics and features of the AVM. For example, the Spetzler-Martin classification has been developed to predict risk of open neurosurgery for patients with AVMs, and accounts for size, location and venous drainage of the AVM.⁶ Furthermore, advanced knowledge of the architectural features of the AVM, including the size and location of the nidus and information on feeding arteries, is essential for operative or endovascular planning. Moreover, some features such as deep location, single draining vein and deep venous drainage are associated with an increased risk of haemorrhage from intracranial AVMs,^{4,7,8} allowing clinicians to identify high-risk patients. As such, imaging plays a pivotal role in the workup of AVMs. While CT angiography and magnetic resonance angiography (MRA) are important in the workup, catheter angiography is considered the gold standard.⁵

Figure 1. A diagram outlining the principle of pseudocontinuous ASL imaging. Inflowing arterial water is labelled by applying an inversion radiofrequency pulse at the neck. A “labelled” image is then acquired. Subsequently, a “control” image is acquired without labelling. The final image is produced by subtracting the “labelled” image from the “control” image. Diagram reproduced with permission from the Functional MRI Laboratory, University of Michigan.



Arterial spin labelling (ASL) is a magnetic resonance (MR) perfusion technique where water in arterial blood is used as an endogenous freely diffusible tracer. ASL involves labelling inflowing arterial blood by applying an inversion radiofrequency pulse proximal to the imaging plane, the nature of which varies according to the specific method employed.⁹ Subsequently, signal from the arterial blood flow in the imaging plane is subtracted from unlabelled control images to provide a subtracted image. As a result, the signal intensity in the resultant image is proportional to blood flow^{10,11} (Figure 1). ASL has emerged as a useful tool in the assessment of a range of neurological conditions where cerebral perfusion is altered, ranging from acute strokes and tumours to vascular malformations and chronic cerebrovascular disease.^{12–15}

To our knowledge, there have been no systematic reviews focused on the utility of ASL in the imaging of AVMs. This systematic review therefore sought to compare the diagnostic performance of ASL in the assessment and characterisation of AVMs against the current gold standard of catheter angiography.

METHODS

Following a predefined protocol (available from the authors on request), we systematically reviewed the peer-reviewed, published literature according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines.¹⁶ We searched two electronic databases using the search terms detailed in the [Supplementary Material 1](#): EMBASE and Medline for articles with no time or language restrictions. Reference lists of included studies were screened to identify further data.

After screening titles and abstracts, we performed a full-text review of remaining articles. The screening and full-text review

were conducted by two independent reviewers (SR and DM) with arbitration in case of disagreement (NK). The reviewers were blinded from each other in the selection process. Inclusion criteria included any primary study that: 1) involved any form of ASL imaging; 2) had adult or paediatric patients with AVMs; and 3) provided a direct comparison with catheter angiography.

During screening and full-text review, a study was excluded once it met any exclusion criterion. The exclusion criteria were always applied in the following order: 1) ASL imaging was not used; 2) no patients with intracranial AVMs were included in study cohort; 3) catheter angiography was not performed for comparison; 4) no appropriate outcome measures reported; and 5) individual case reports or conference abstracts.

Outcomes were categorised according to three domains: overall detection (including accuracy of presence, location and size), architectural features (including nidus, feeding arteries and draining veins) and haemodynamic features (including flow and arteriovenous shunting). We extracted any data that allow direct comparison of ASL performance with catheter angiography in these domains. We recorded information in a standardised database on the following: study design, patient characteristics, sample size, outcome measures and associated statistical significance, ASL protocols (including labelling method, MR field strength and sequence parameters) and information pertaining to the quality assessment outlined below.

We gave a descriptive analysis of the outcomes and provided a qualitative analysis of the data. We did not pool outcomes due to the marked heterogeneity in study outcome measures and populations.

Using an adapted QUADAS-2 tool,¹⁷ we evaluated the quality of studies according to five categories, each reflecting a key domain of QUADAS-2:

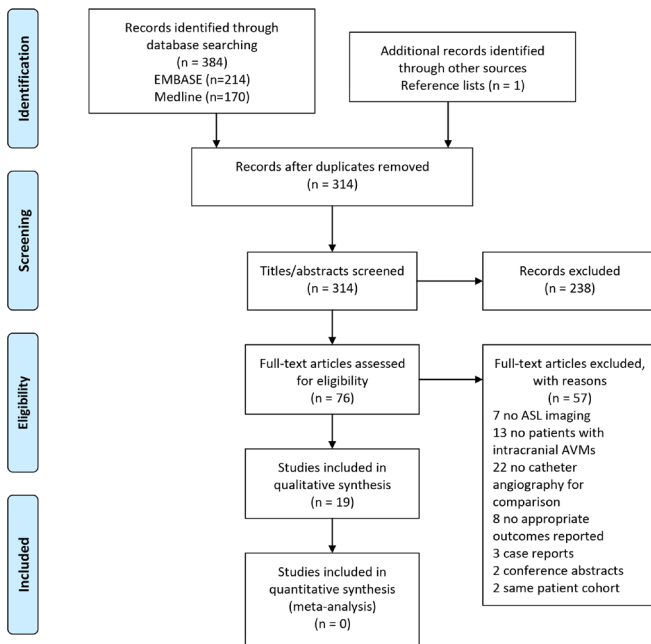
- Study design (under the domain “patient selection”)
- Patient enrolment method (under “patient selection”)
- Risk of individual interpreter subjectivity (under “index test” and “reference standard”)
- Risk of recall bias (under “index test” and “reference standard”)
- Time elapsed between ASL imaging and catheter angiography (“flow and timing”)

Details of how each study was assessed against each criterion is outlined in the [Supplementary Material 1](#).

RESULTS

Of 314 unique records, we excluded 238 by abstract/title screening and 57 by full-text review (Figure 2). Nineteen studies met the inclusion criteria and provided outcomes on 289 patients with intracranial AVMs. There were no patients with AVMs located in other anatomical sites which met the inclusion criteria. A summary of patient characteristics and outcome measures by study is provided in [Table 1](#).

Figure 2. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram outlining the selection process for studies



Description of studies

The majority of studies were retrospective in study design ($n = 11$, 57.9%),^{18–28} and the remaining were prospective comparative studies ($n = 8$, 42.1%).^{29–36} Sample sizes in studies were relatively small, with a mean of 15.2 patients per study (range: 2–53). Labelling methods and magnetic field strengths used in each study are outlined in [Table 1](#). Other details of MR parameters used were not as consistently reported and are reported in the [Supplementary Material 1](#).

Most studies did not employ restrictions on patient or AVM characteristics, but tended to primarily enrol a large adult population ($n = 10$, 52.6%). Only two studies (10.5%) focused exclusively on paediatric patients, with a combined sample size of 40 patients.^{19,24} Some had focused on the follow-up for procedures to treat the AVM ($n = 4$, 21.1%), namely poststereotactic radiosurgery^{18,22,25} and postembolisation³² with a total of 39 patients. Two studies only included patients with untreated AVMs,^{26,27} one of which recruited newly diagnosed AVMs.²⁶ One study only recruited patients with small AVMs (defined as <2 cm) and was combined with patients with arteriovenous fistulas (AVFs).²³

Study quality

The majority of studies were retrospective and were therefore deemed relatively low quality in this category ($n = 11$, 57.9%). Only two studies (10.5%) described recruitment methods intended to minimise selection bias, by using consecutive patients.^{28,33} The vast majority of studies used at least two interpreters to assess the ASL imaging and were therefore deemed high quality in this category ($n = 17$, 89.5%). Most studies had described sufficient blinding to be assessed as high quality ($n = 11$, 57.9%). ASL imaging and catheter angiography were performed within 6 months of one another in most studies ($n = 14$, 73.7%), whereas

timing was not reported in the remaining five studies. A full list of study quality assessments is provided in [Table 2](#).

Detection of AVMs

Three studies demonstrated a sensitivity of 78%,²³ 95.1%²⁸ and 98%,³⁴ respectively, in detecting the overall presence of an AVM, with the limitation that the former reflected a mixed cohort of patients with small AVMs and AVFs.²³ Moreover, two studies investigating the identification of AVMs following stereotactic radiosurgery demonstrated 100% sensitivity in detecting residual AVMs,^{18,25} and high specificities of 95%²⁵ and 100%.¹⁸

Four studies evaluated concordance in Spetzler-Martin classifications between ASL and catheter angiography.^{21,28,35,36} There was an overall moderate intermodality agreement among three studies,^{21,28,36} with Cohen's κ coefficients ranging from 0.43²¹ to 0.89.³⁶ The fourth showed high concordance at 87.5% at 7T, reducing to 50% at 3T. The discrepancies at both field strengths were solely due to inaccurate or inadequate delineation of venous drainage.³⁵ Finally, one study found a statistically significant, moderately positive correlation between overall AVM signal intensity of the AVM and size of the AVM measured during catheter angiography ($r = 0.561$, $p < 0.001$),²⁰ irrespective of whether the AVM had been previously treated or not.

Angioarchitectural features of AVMs

A number of studies assessed performance in identifying arterial feeders ($n = 7$, 36.8%).^{26,27,29–31,33,36} Across five studies,^{26,29–31,33} sensitivity in this domain ranged from 84.6%³³ to 100%³¹ (median: 91%). Across two studies, specificity ranged from 93.33%³³ to 100%.²⁶ Good diagnostic performance was demonstrated for both standard and custom labelling efficiencies, with an area under the curve value of 0.94 and 0.96, respectively, ($p < 0.01$).³³ Interestingly, one study identified an arterial feeder on ASL which was not accessible on catheter angiography due to altered vasculature.³¹ The final two studies revealed high intermodality agreement for delineating arterial feeders at 0.85³⁶ and 0.88,²⁷ respectively.

Fewer studies assessed venous drainage ($n = 5$, 26.3%)^{24,26–28,36} and showed relatively lower performance in this domain. One study found the mean sensitivity and specificity for the identification of draining veins by vessel selective ASL to be 62 and 100%, respectively. Meanwhile, non-vessel selective ASL had slightly higher sensitivity at 79% but lower specificity at 93%.²⁶ Moreover, in a study of paediatric patients, the median number of draining veins detected on DSA was approximately twice as many as on ASL (3.63 on DSA versus 1.76 on ASL, $p < 0.05$).²⁴ Three studies showed similar intermodality agreement for venous drainage patterns at 0.72,²⁸ 0.82³⁶ and 0.80 (95% CI: 0.45–1.00),²⁷ respectively, with the latter marginally lower compared to both arterial drainage and nidus size.²⁷ One of these studies demonstrated markedly superior intermodality agreement an acquisition window over two cardiac cycles.³⁶

AVM nidus

Some studies reported outcome measures on the AVM nidus ($n = 6$, 31.6%).^{19,26–28,30,36} Two studies demonstrated 100% accuracy

Table 1. Summary of results for studies comparing the performance of ASL imaging in the assessment of intracranial AVMs with catheter angiography

Study	Study design	Labelling method/MR field strength	Patient characteristics	Sample size	Outcome measure	Outcome value	Statistical significance
Kuluk 2010	Prospective	Selective PASL / 3T	Symptomatic AVMs	16	Sensitivity in identification of feeding arteries in combination with MRA additional functional/anatomical information	96–25%	
Amponsah 2012	Retrospective	PASL / N/R	γ knife radiosurgery follow up	9	Sensitivity to incomplete obliteration sensitivity to complete obliteration*	100/100%	95% CI: 0.66–1
Blauwblomme 2015	Retrospective	pCASL / 1.5T	Paediatric (untreated or partially treated AVMs). Mean age: 10.8 (range 3.6–17)	21	Accuracy of nidus location	100%	
Wu 2014	Prospective	pCASL / 3T	Previously diagnosed AVMs	3	Sensitivity to arterial pedicles Accuracy of nidus location	87.5/100%	
Jensen-Koendering 2015	Prospective	Supersensitive pCASL / 1.5T	Clinical cases. Age range 20–65. 1F	2	Sensitivity in identification of feeding arteries	100%	
Sunwoo 2015	Retrospective	pCASL / 3T	Treated & untreated AVMs. Mean age: 37.4 (range 14–72), 17F	40	Correlation between AVM signal intensity on ASL and degree of early vein opacification on DSA Correlation between AVM signal intensity and size on DSA	0.638 0.561	p < 0.001 p<0.001
Schubert 2018	Retrospective	pCASL / mixed 1.5 & 3T	Demonstrating AV shunting. Mean age: 58.5 (41–75), 5F	8	Agreement with DSA Spetzler-Martin classification (Cohen's unweighted κ) Sensitivity to AV shunting (reader 1/2) Specificity to AV shunting (reader 1/2)	Reader 1: 0.43 Reader 2: 0.6 100% / 91.7 100% / 100%	
Kodera 2017	Retrospective	pCASL / 3T	Stereotactic radiosurgery follow up. Mean age: 48.7 (range 28–80), 3F	7	Sensitivity to disappearance of AV shunting	100%	
Le 2012	Retrospective	pCASL / 1.5T	Small AVMs (<2cm) combined with 8 AVFs. Combined mean age: 58 (range 11–69), 6F	15 (7 with AVMs)	Sensitivity of venous ASL signal for presence of AVM/AVF on DSA** Specificity of above** Positive predictive value of above** Negative predictive value of above**	78–85% 8874%	95% CI: 63–89% 68–95% 73–96% 57–87%
Suazo 2012	Prospective	PASL / 3T	Post-embolisation. Mean age: 40 (range 15–51), 3F	8	Reduction in signal of AVM on ASL for 10–20% shunt reduction estimated on DSA (four patients) Reduction in signal for 30–50% shunt reduction (two patients) Reduction in signal for 80–100% shunt reduction (two patients)	–6%† to 14–25 to 60%–69 to 76%	

(Continued)

Table 1. (Continued)

Yu 2014	Prospective	Vessel-encoded pCASL / 3T	Consecutive patients with AVMs. Mean age: 32.8 (range 13–47), 8F	18	Standard labelling efficiency: Sensitivity in identification of feeding arteries: Specificity of above Area under the curve (AUC) Custom labelling efficiency: Sensitivity in identification of feeding arteries Specificity of above Area under the curve (AUC)	84.62–93.33% / 0.935 89.74–93.33% / 0.957	$p < 0.01$ $P < 0.01$
Nabavizadeh 2014	Retrospective	PASL / 3T	Paediatric patients with angiographically confirmed AV shunting. Mean age: 9.2 (1 day – 17.5), 8F	19	Median number of draining veins on DSA / median number on ASL Sensitivity in detecting AV shunting	3.63 / 1.76 100%	$p < 0.05$
Heit 2019	Retrospective	pCASL / mixed 1.5 & 3T	Stereotactic surgery follow up. Mean age: 29 (range 14–55), 12F	15	Sensitivity of venous signal for residual AVM Specificity of above Positive predictive value of above Negative predictive value of above	100–95% / 98.100%	95% CI: 90–100% / 70–100% / 90–100% / 80–100%
Fujima 2016	Retrospective	PASL / 3T	Newly diagnosed AVMs. Mean age: 32.3 (range 5–69), 4F	12	Mean sensitivity for identification of feeding arteries (vessel selective / non-vessel selective) Mean specificity of above Mean positive predictive value Mean negative predictive value Mean sensitivity for identification of draining veins (vessel selective / non-vessel selective) Mean specificity of above Mean positive predictive value Mean negative predictive value Nidus size on DSA / vessel selective / non-vessel selective (mean \pm SD, mm) Error values of assessment of % contribution of feeding arteries to overall blood flow of AVM. DSA / vessel-selective (mean \pm SD, %)	98% / 91–100% / 95.5100% / 84.599.5% / 97.5% 62% / 79100% / 93100% / 96.552% / 65% 36.8 \pm 13.1 / 34.4 \pm 11.8 / 34.7 \pm 11.3 27.1 \pm 5.7 / 7.1 \pm 3.9	$p = 0.82$ $p < 0.05$
Hodel 2017	Prospective	pCASL / 3T	Suspected AV shunting. Mean age: 47.4 (range 11–81, 40F)	53	Sensitivity for presence of AVM Sensitivity in identification of AV shunting Specificity of above Positive predictive value of above Negative predictive value of above Area under the curve	98.95% 90.95% 90% / 0.92	95% CI: 90–100% / 78–100% / 87–99% / 73–98% / 0.84–0.97
Iryo 2016	Retrospective	pCASL / 3T	Untreated AVMs. Mean age: 39.5 (range 7–65), 4F	6	Intermodality agreement for nidus size (Cohen's k) Intermodality agreement for arterial feeders Intermodality agreement for venous drainage	1.00 0.88 0.80	95% CI: 1.00–1.00 / 0.671–1.00 0.449–1.00
Cong 2018	Prospective	PASL / 3 & 7T	Mean age: 25.1 \pm 13.2, 6F	8	Agreement with DSA Spetzler-Martin classification at 3 T / 7 T Agreement with venous drainage pattern on DSA at 3 T / 7 T	50% / 87.5–50% / 87.5%	

(Continued)

Table 1. (Continued)

Togao 2019	Retrospective	PASL / 3T	Consecutive patients with AVMs, Mean age: 31.1 (range 9–63), 10f	21	Sensitivity for presence of AVMs; Mean intermodality agreement for Spetzler-Martin classification (Cohen's κ); Mean intermodality agreement for venous drainage patterns; Nidus size on DSA / ASL observer 1/ASL observer 2 (mean \pm SD, mm)	95.1%; 0.748 0.718 32.1 \pm 23.3/27.2 \pm 23.3/29.9 \pm 20.4	Not significant
Raouf 2014	Prospective	PASL / 3T	Mean age: 42.0 \pm 15.6, 9F	16	Intermodality agreement for nidus size (Cohen's κ) over two cardiac cycles; Intermodality agreement for arterial feeders; Intermodality agreement for venous drainage; Intermodality agreement for Spetzler-Martin classification	1.00 0.85 0.82 0.89	95% CI: 1.00–1.00, 0.65–1.00 0.59–1.00 0.71–1.00

AUC, Area Under the Curve; AVF, arteriovenous fistula; CI, confidence interval; DSA, digital subtraction angiogram; MRA, magnetic resonance angiogram; NR, not reported; PASL, pulsed arterial spin labelling; pCASL, pseudo continuous arterial spin labelling; SD, standard deviation; T, Tesla.
^aDefined as complete absence of nidus and draining veins.
^bOutcomes reported are a combination of AVMs and AVFs as data were not stratified according to type of malformation
^c-.6% denotes a slight increase in AVM ASL signal observed in one patient in this cohort
^dCustom labelling method involved altering ASL imaging parameters according to AVM characteristics in individual patients. Standard labelling method was a standardised ASL imaging protocol applied uniformly for each patient, and is outlined in the supplementary appendix. Sensitivities and specificities reported are calculated at the optimal cut-off of supply fraction to achieve a targeted balance between sensitivity and specificity.
^eOutcome measures were reported as a mean of two independent readers.

of ASL in determining nidus location from a combined cohort of 24 patients,^{19,30} 21 of whom were paediatric patients. Two studies showed no significant differences in nidus size across DSA and ASL.^{26,28} Similarly, two studies found excellent intermodality agreement between ASL and catheter angiography for nidus size, with an overall Cohen's κ value of 1.00 from a total of 22 patients.^{27,36}

Haemodynamic features of AVMs

Some studies reported haemodynamic outcome measures of AVMs, specifically of AV shunting ($n = 6, 31.6\%$).^{20,21,24,25,32,34} Sensitivity in detecting AV shunting ranged from 91.7%²¹ to 100%,^{21,24} including 100% sensitivity in an exclusive cohort of 19 paediatric patients.²⁴ Specificity was measured by two studies and ranged from 90%³⁴ to 100%.²¹ Importantly, the study with the largest sample size in this review (53 patients) showed robust diagnostic performance of ASL in detecting AV shunting.³⁴ From a sample size of eight patients, one study demonstrated good agreement in quantifying AV shunt reduction postembolisation with operator-based estimates during catheter angiography.³² Similarly, a further study showed 100% sensitivity in detecting the disappearance of AV shunting from a cohort of seven patients following on from stereotactic radiosurgery.²²

DISCUSSION

Nineteen studies evaluated the diagnostic performance of ASL in the characterisation of intracranial AVMs in comparison with catheter angiography. Findings suggest that ASL has promising diagnostic potential, particularly in ascertaining the location of the AVM and the nidus, determining the presence of AV shunting and identifying arterial feeders. Of all outcome measures, the evidence for arterial feeders^{26,27,29–31,33,36} and AV shunting^{20,21,24,25,32,34} are the strongest, with several studies showing consistently high diagnostic performance in these domains. Furthermore, there is some evidence that ASL may provide a robust non-invasive imaging alternative to catheter angiography in assessing the response to treatment following stereotactic radiosurgery and embolisation. However, there is evidence from five studies that suggests inferior performance in the characterisation of venous drainage. In addition, ASL appears to be a usable imaging tool, with high interobserver agreement,^{20,23,25–27,33–35} adequate diagnostic quality^{27,33,35} and acceptable scan times (with a mean reported time of 5 min). However, the strength of the evidence base is limited by small sample sizes and relatively low quality in some domains (particularly study design and patient recruitment).

Although heterogeneity in ASL labelling methods prevented analysis of its effects on the imaging of AVMs, there is preliminary evidence that increased field strength to 7T³⁵ and electrocardiogram gating over two cardiac cycles as opposed to one³⁶ can improve the diagnostic performance of ASL. Furthermore, although vessel-selective ASL confers the theoretical advantage of imaging AVMs according to their specific vascular territory, evidence from three studies demonstrates no significant difference in performance to non-selective methods.^{29,31,33}

Two further conference abstracts also addressed our research question.^{37,38} The first study showed that ASL was able to

Table 2. A summary of quality assessment of studies included in qualitative synthesis

Study	Study design	Patient enrolment	Interpreter subjectivity	Confirmation bias (blinding)	Delay between modalities
Kukuk 2010	High	Low	High	High	High
Amponsah 2012	Low	Low	Low	Low	Unclear
Blauwblomme 2015	Low	Low	High	Unclear	High
Wu 2014	High	Low	High	Unclear	High
Jensen-Kondering 2015	High	Low	High	Unclear	Unclear
Sunwoo 2015	Low	Low	High	High	High
Schubert 2018	Low	Low	High	High	Unclear
Kodera 2017	Low	Low	High	Unclear	Unclear
Le 2012	Low	Low	High	High	High
Suazo 2012	High	Low	Unclear	Unclear	High
Yu 2014	High	High	High	High	High
Nabavizadeh 2014	Low	Low	High	High	High
Heit 2019	Low	Low	High	High	High
Fujima 2016	Low	Low	High	High	High
Hodel 2017	High	Low	High	High	High
Iryo 2016	Low	Low	High	High	High
Cong 2018	High	Low	High	Unclear	Unclear
Togao 2019	Low	High	High	Low	High
Raoult 2014	High	Low	High	High	High

Quality assessment was carried out using an adapted QUADAS-2 tool. A colour-coded system is used to represent the quality of the study under each domain, as opposed to risk of bias. Green is used if the study quality was high, red if the study quality was low and grey if there was insufficient information reported to formulate a judgement.

successfully identify all three AVMs in patients with hereditary haemorrhagic telangiectasia, two of which were smaller than 1 cm.³⁷ Conversely, the second contrastingly showed a lower sensitivity of 72% and intermodality agreement with DSA of only 0.39 for ASL among paediatric patients in post-treatment AVM surveillance. However, specificity was 100% and sensitivity rose to 92% when using additional techniques that combined ASL with spoiled gradient recalled echo.³⁸ Moreover, ASL imaging has been shown to be useful in diagnosing paediatric cervicofacial AVMs by demonstrating increased lesional flow.³⁹

ASL may confer several advantages over both catheter angiography and conventional MRA. First, the use of intravenous gadolinium in some conventional MRA techniques may be avoided as ASL uses water as an endogenous tracer.¹³ This is of clinical importance as ASL may offer an alternative option for patients with renal impairment who are at risk of nephrogenic systemic fibrosis,⁴⁰ and in other circumstances where gadolinium poses risks, such as in paediatric patients in the first year of life and during pregnancy.^{41,42} Second, ASL may offer a safer, non-invasive alternative to catheter angiography in select cases, obviating the risks posed by the latter.^{43,44} Third, ASL provides a functional AVM assessment that provides an objective,

quantitative measure of flow. Fourth, ASL may identify some arterial feeders not detected on catheter angiography³¹ and may offer better characterisation of low-flow segments of the nidus.³² Fifth, strong pressure injection of contrast agent during catheter angiography may result in an overestimation in the proportion of blood flow in the nidus, due to reflux from other feeding arteries. This phenomenon may have been reflected in some studies in our review.^{26,32} ASL may mitigate for this by providing a more physiological indication of cerebral blood flow. Sixth, ASL may occasionally be useful in identifying AVMs that may otherwise be obscured on DSA by mass effect secondary to intracerebral haemorrhage.²³

In contrast, there are a number of disadvantages in using ASL. The reduced reliability of ASL for venous drainage may be accounted for by the recovery of spin inversion in arterial water during its transit, such that the signal reduces by the time it enters venous drainage.⁴⁵ Furthermore, there was interstudy variation in the MR parameters employed in this review. Although no general trend was identified in whether the variation in these parameters significantly affected outcome measures, there were too few studies to formally assess this. Indeed, it has been shown that altering parameters such as postlabelling delay time can change

nidal, venous and gray matter perfusion.⁴⁶ The sensitivity of ASL in evaluating small AVMs, low flow AVMs, small calibre arterial feeders and draining veins is also not clear from current evidence, and may represent another potential issue.

Moreover, AVMs in particular locations such as the apical cranial convexity may be more difficult to detect on ASL due to greater loss of signal as the labelled blood travels further from the labelling plane.²¹ There may also be an underestimation of total blood flow in AVMs on ASL, as regions of interests may include not only the high-flow nidus but also the arterial feeders and draining veins, resulting in an average value for flow.³² Another caution in the immediate postintervention period is that ASL may underestimate angiographically confirmed complete AV shunt occlusion, which may be due to dilatation of proximal segments of previous feeding arteries³² or changes in autoregulation.⁴⁷ However, this can be mitigated by comparative use of MRA. Furthermore, ASL interpretation can be hindered by inhomogeneities in certain vessel territories³¹; hyperintensity secondary to conditions such as seizures and luxury perfusion⁴⁸; and large changes in cerebral blood flow that occur with age.⁴⁹

Review limitations

First, the evidence we present is limited by the small sample sizes of many studies. Another consequence of this is that statistical significance was inconsistently reported, rendering interpretation of some data difficult. Second, the majority of studies were retrospective and of the remaining prospective studies, only one reported a robust recruitment strategy. This also limits the strength of the

evidence base. Third, we could not evaluate the effect of inter-study variation in labelling methods and MR sequence parameters. Fourth, although a few studies did directly compare ASL with other MR imaging modalities, this was not the focus of our review. Finally, the study populations and the outcome measures varied widely, precluding our ability to pool data for meta-analysis.

CONCLUSIONS

Taken together, this review provides preliminary evidence on the reliability of ASL in evaluating intracranial AVMs. Although the quality of current evidence and technical limitations of ASL suggest that it will not replace conventional catheter angiography, it shows a promising role of ASL imaging in the workup of AVMs and their follow-up after treatment. There is sufficient evidence to justify larger scale prospective studies dedicated to assessing the diagnostic performance of ASL. Furthermore, there was no literature on ASL imaging of truncal or peripheral AVMs, highlighting another area for future research.

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CONFLICTS OF INTEREST

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