



Preprocedural Imaging

A Review of Different Radiological Factors Affecting the Outcome of Thrombectomy

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Abstract

Background Endovascular treatment (EVT) has strong evidence for its effectiveness in treatment of acute ischemic stroke (AIS); however, up to half of the patients who undergo EVT still do not have good functional outcomes. Various prethrombectomy radiological factors have been shown to be associated with good clinical outcomes and may be the key to better functional outcomes, reduced complications, and reduced mortality. In this paper, we reviewed the current literature on these imaging parameters so they can be employed to better estimate the probability of procedural success, therefore allowing for more effective preprocedural planning of EVT strategies.

We reviewed articles in the literature related to imaging factors which have been shown to be associated with EVT success. The factors which are reviewed in this paper included: anatomical factors such as 1) the type of aortic arch and its characteristics, 2) the characteristics of the thrombus such as length, clot burden, permeability, location, 3) the middle cerebral artery features including the tortuosity and underlying intracranial stenosis, 4) perfusion scans estimating the volume of infarct and the penumbra and 5) the effect of collaterals on the procedure. The prognostic effect of each factor on the successful outcome of EVT is described. The identification of preprocedural thrombectomy imaging factors can help to improve the chances of recanalization, functional outcomes, and mortality. It allows the interventionist to make time-sensitive decisions in the treatment of acute ischemic stroke.

Keywords Ischemic stroke · Endovascular treatment · CT · MRI · Acute

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Introduction

Endovascular treatment (EVT) has strong evidence for its effectiveness in the treatment of acute ischemic stroke (AIS), however, it is unable to achieve recanalization in approximately 20% of patients [1–3]. Moreover, up to half of EVT patients do not have a good functional outcome at 3 months and this includes patients with good reperfusion [4]. Radiological factors which are associated with good clinical outcome have become a hot topic for research in EVT. For example, a hyperdense vessel sign is associated with a better rate of recanalization, [5] and complete recanalization with a single pass of the device has been shown to have better clinical outcome [6]. More effective EVT strategies can be implemented if the probability of procedural success with different techniques can be estimated before the start of the procedure. In this review we therefore looked at the various preprocedural radiological variables in the literature which are associated with more efficient recanalization and better outcomes and how they can affect the decision making in EVT (Table 1).

Arch Characteristics

Aortic Arch Types

The type of aortic arch has an impact on the procedural time and the eventual functional outcome. A computed tomography angiogram (CTA) can be used to facilitate preprocedural planning of an EVT procedure. Examples of important features include the aortic arch type (aortic arch types I–III), the common carotid artery (CCA)/innominate take-off angle from the arch, and the cranial-to-caudal distance from the origin of the innominate artery to the top of the aortic arch (CCIA).

The association between unfavorable aortic arch types (type II or III) (Fig. 1) and longer procedural time, with more ischemic events in patients undergoing carotid stent placement, has been established in several studies [7–10]. The take-off angle between vessels is defined as the angle of the vessel off the aortic arch in reference to a straight line down the curve of the spine. For right-sided stroke the innominate angle can be calculated and for left-sided stroke, the CCA angle can be calculated. In a retrospective study by Knox et al. [11]; statistically significant longer groin to reperfusion time was associated with larger take-off angles and larger CCIA.

Similarly, in a study by Kaymaz et al. [12] there was a significant correlation between carotid access time and vessel tortuosity of each evaluated vessel segment. Carotid access time was most significantly affected equally by the take-off angle of the left CCA, or the take-off angle of the

brachiocephalic trunk. A take-off angle of the left CCA of $>60^\circ$ or the brachiocephalic trunk of $>100^\circ$ was associated with slower carotid access times. Carotid access time was almost doubled in the event of a bovine aortic arch variant, which refers to the configuration of the aortic arch in which the left common carotid artery origin is moved to the right and merges with the origin of the innominate artery. The study also found that a carotid access time of 25 min or less translated into an association with successful recanalization in both right and left hemisphere AIS.

Finding difficult aortic anatomical features on CTA may prompt consideration of alternative routes other than femoral access in an attempt to minimize puncture to reperfusion time and achieve better functional outcomes. This can be radial or even direct carotid puncture depending on the situation.

Arch Characteristics Affecting the Transradial Approach

There has been a recent increased interest in transradial access with a reduction in serious access site complications, decreased cost and improved patient satisfaction. Khan et al. [13] identified factors statistically associated with increased procedural difficulty which included 1) tortuosity in subclavian innominate anatomy (defined as double subclavian-innominate curve), resulting in a loop in the catheter and reduced torquability, 2) presence of a left common carotid artery loop (Fig. 2), with inability to maintain a stable position, 3) larger diameter of the aortic arch, making reforming a Simmons catheter more difficult, 4) presence of a proximal radial loop, which was associated with a higher conversion to femoral access and 5) the presence of an acute left or right subclavian-vertebral angle (Fig. 3), which was associated with increased fluoroscopy time per vessel to access the vertebral arteries [13]. Additional important factors to consider which did not reach statistical significance included a type II or III aortic arch, as well as a right aberrant subclavian artery or “artery lusoria” with difficulty reforming the Simmons catheter and near impossibility to cannulate the great vessels from the right side. From these various characteristics, the authors created a transradial angiography (TRA) grading scale [13] (supplemental Table 1), with points allocated for each of the anatomical variables to estimate the difficulty using the transradial approach. Finally, in a study by Mori et al. that used balloon guide catheters for transbrachial access. They found that in left sided large vessel occlusions (LVO) on CTA, a bovine aortic arch or a nonbovine aortic arch with take-off angles $<23^\circ$ predicts higher rates of access, whereas in right sided LVOs, a take-off angle of $\geq 25^\circ$ predicts higher rate of access [14].

Table 1 Radiological signs and their implications

Radiological signs	Clinical implications
<i>1. Aortic arch signs:</i>	
Aortic arch type II or type III	Longer procedural times, more ischemic events when stenting the carotid
Common carotid angle (CCA) or innominate take off angle	Take-off angle of the left CCA $>60^\circ$ or the brachiocephalic trunk of $>100^\circ$ was associated with slower carotid access times. A CCA 10° angle increase corresponds to a 5 min 17 s increase in the procedure time
Cranial to caudal distance (CCIA) from innominate origin to top of aortic arch	Increase in procedure time, with a 5-mm increase in the CCIA span corresponding to a 2 min 59 s increase
Bovine aortic arch variant	Carotid access time is doubled
Aortic dissection	Increased risk of complications
Extending CTA window to include the heart	Identification of cardioembolic sources such as ventricular thrombi and atrial appendage
<i>2. Aortic arch signs for radial access:</i>	
Double subclavian-innominate curve	Reduced torquability with loss of distal catheter control
Left common carotid artery loop	Difficulty maintaining a stable position without herniating back into the aortic arch
Larger diameter of the aortic arch	Difficulty in reforming a Simmons catheter
Proximal radial loop	Higher rate of conversion to femoral access
Acute left or right subclavian vertebral angle	Increased vertebral artery access time
Right aberrant subclavian artery or “artery lusoria”	Difficulty in reforming a Simmons catheter, impossible to access the great vessels from the right side
<i>3. Clot characteristics</i>	
Thrombus length >8 mm	Inability to recanalize with IV tPA, worse functional outcomes, SICH and mortality with IA thrombectomy
Clot burden score	Higher scores associated with quicker procedures, better outcomes with stent retrievers
Clot location	Distal middle cerebral artery (MCA) clots have better reperfusion than internal carotid artery (ICA) clots
Clot permeability	More permeable clots have better functional outcomes with Intravenous tPA and/or thrombectomy
Dense vessel sign (CT) or SWI sign (MRI)	Associated with red blood cell predominant clots, A negative sign with a truncal type occlusion may indicate underlying intracranial atherosclerotic stenosis
Calcified thrombus	Poorer recanalization rates and higher mortality
<i>4. Middle cerebral artery characteristics</i>	
MCA top-to-bottom (TB) distance	TB distance of >8.8 mm is associated with postprocedural hemorrhage
Truncal Vs Embolic occlusions	Truncal occlusions are associated with underlying intracranial atherosclerotic stenosis. Glycoprotein IIb/IIIa blocker use or rescue stenting with or without angioplasty may be considered early
<i>5. Infarct and penumbra volume</i>	
Alberta stroke program early CT score (ASPECTS) score	10-point score with lower scores associated with poorer functional outcomes and higher mortality
Diffusion weighted imaging (DWI) volume	DWI >70 ml is associated with poor outcomes regardless of treatment, DWI volumes <50 ml have better functional outcomes with thrombectomy
DWI-FLAIR mismatch	DWI-FLAIR mismatch has better recanalization and better functional outcomes. Similar outcomes even in patients with DWI-FLAIR mismatch and unknown time of onset
Perfusion imaging parameters (CBF, CBV, Tmax)	Relative CBF $<30\%$, absolute CBV <1.8 ml/100 g, absolute CBF <15 ml/100 g/min or an absolute Tmax >10 s can be used estimate the core infarct. Tmax >6 s is typically used to estimate the penumbra
<i>6. Collateral scoring</i>	
Tan and Maas CT angiogram grading	50% of the affected area is associated with better functional outcomes
Calgary multiphasic CT-angiogram grading	Better collateral grades are associated with good functional outcomes
Asymmetrical deep medullary veins on Susceptibility weighted imaging (SWI) or gradient reduced echo (GRE)	Asymmetrical deep medullary veins seen on MRI are associated with poor functional outcomes
Relative CBV (rCBV) or perfusion collateral index	rCBV is multiplied by the volume of Tmax of 2–6 s is a surrogate of good collaterals and associated with good functional outcomes
Hypoperfusion intensity ratio (HIR)	Ratio of tissue with a time-to-maximum (Tmax) >10 s and Tmax >6 s. A HIR of 0.4 or less is associated with poorer collaterals and poorer outcomes

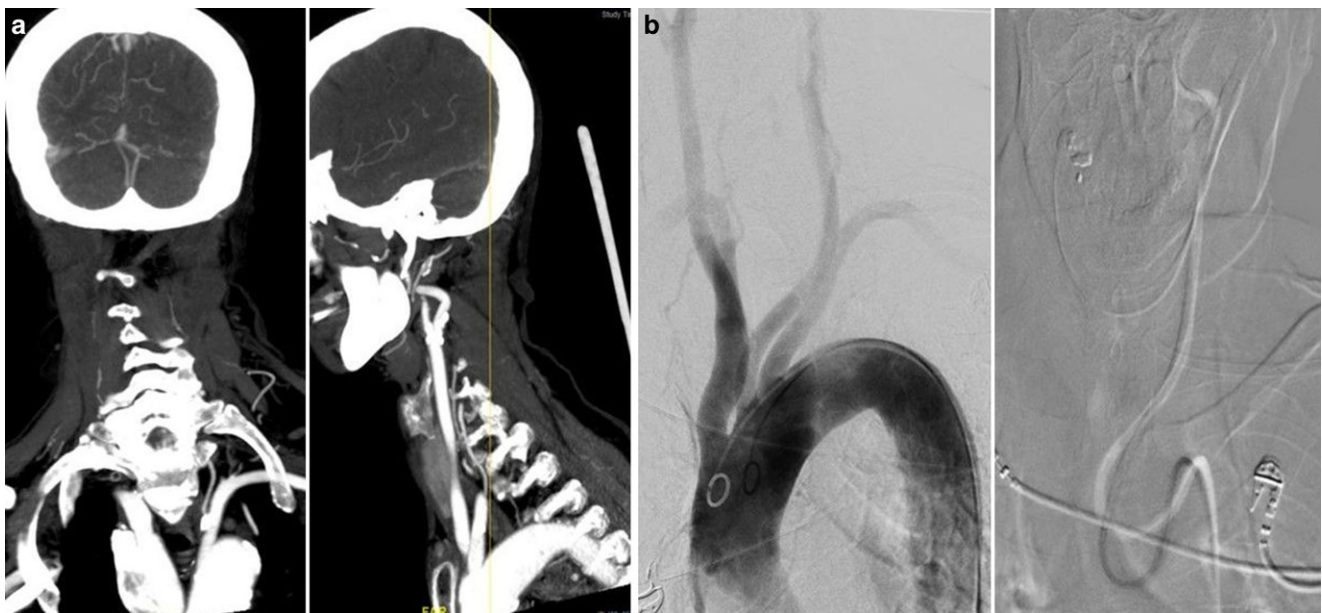


Fig. 1 **a** Type 3 aorta in coronal and sagittal views of CT angiogram. **b** Type 3 aorta in digital subtraction angiography

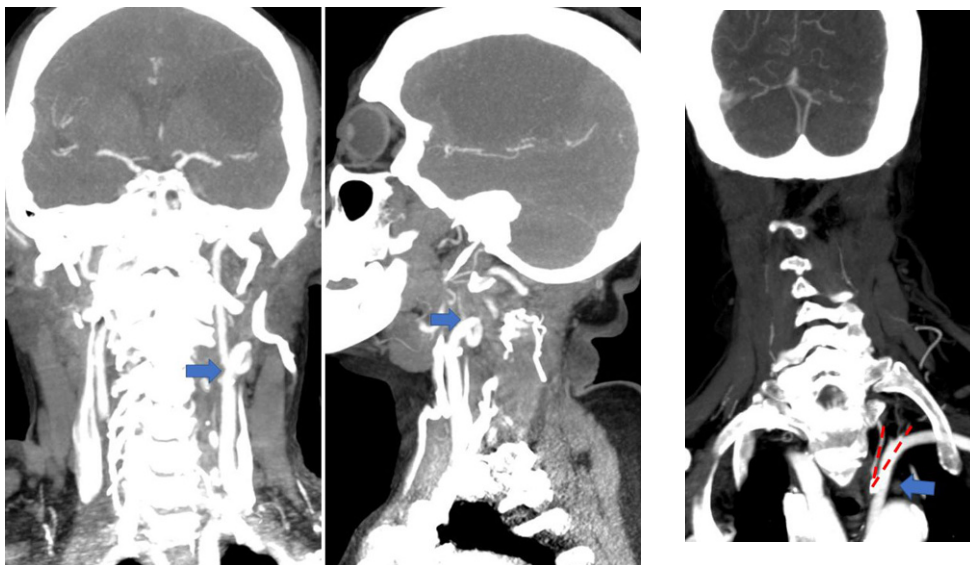


Fig. 2 Presence of left carotid loop on the coronal and sagittal views of CT angiogram (*arrow*)

Fig. 3 Acute left subclavian-vertebral angle seen on coronal view of CT angiogram (*arrow*)

Aortic Dissection and Cardiac Thrombi

The incidence of aortic dissection was noted to be 1 in 200 code stroke patients and 1 in 125 patients of patients with acute ischemia [15]. This can reduce unnecessary complications which can occur if the interventionist is unaware of a type A dissection. Furthermore, extending the imaging lower to encompass the heart can help in determining if there are any embolic sources of stroke from the heart without an increased contrast dose. A non-gated CT angiogram starting below at the heart can identify embolic sources,

such as a left ventricular thrombus or an atrial appendage. A CTA can therefore evaluate the heart and ascending aorta together with the mandatory imaging of the caroticovertebral circulation and has potential to prognosticate risk following AIS and impact the subsequent treatment modality [16].

Clot Characteristics

Thrombus Length—THERAPY Trial

Thrombus length (TL) was one of the first imaging parameters evaluated for the treatment for anterior circulation LVO AIS. In the THERAPY trial [17], intra-arterial thrombectomy plus intravenous recombinant tissue plasminogen activator (IV TPA) versus IV TPA alone in TL >8 mm was evaluated. The cut-off of 8 mm was selected based on the previous findings that IV TPA has low ability to recanalize vessels with a thrombus length exceeding 8 mm [18]. In the THERAPY trial, a longer TL was associated with higher 90-day modified Rankin Scale (mRS) (OR 1.24 per 5-mm TL increment; 95% confidence interval, CI: 1.04–1.52; $P=0.02$). In addition, longer TL was also associated with more serious adverse events, more symptomatic intracranial hemorrhage (SICH) and increased mortality, despite TL not being significantly associated with successful refusion (thrombolysis in cerebral infarction [TICI] 2b–3). Longer TL was also associated with longer procedural times for the patients undergoing thrombectomy. The investigators also noted that longer thrombi were found more in the internal carotid artery (ICA) occlusions than middle cerebral artery (MCA) occlusions and were associated with lower Alberta Stroke Program Early CT (ASPECT) score and poorer collaterals. While few trials have been performed in long TL cohorts or large clot burdens, it may be logical to start with both an aspiration catheter and stent-retriever combination to improve reperfusion chances and many centers use both modalities from the start.

Location and Clot Burden Scores

In a large series of 408 EVT patients, smaller clots on preprocedural imaging with higher clot burden scores (CBS) had quicker procedural times and each increase in CBS led to a decrease of 8 min of procedural time [17, 19], which translated into superior functional outcomes at 3 months [19]. For AIS patients with higher CBS, stent retrievers had an increased rate of favorable functional outcomes compared with other modalities. Longer thrombi were also more difficult to remove, with no difference in the type of EVT modality used. In the same study, the location of the clot also affected the outcomes: compared to ICA occlusions, more distal M1 clots were associated with a better reperfusion as well as better outcomes. Importantly, lower CBS, proximal ICA occlusions, and longer clot length were all associated with increased mortality [17, 19–22].

Thrombus Permeability

The density or physical porosity of the thrombus varies within a range but it correlates to some extent to the amount of contrast squeezing between the platelets, fibrin filaments, and the bound red blood cells inherent in a clot. This is termed the permeability or perviousness of the thrombus and more permeable thrombi have been associated with better functional outcomes [23]. This may be in-part due to the potential higher success rate of intravenous tPA when used as a bridging modality in AIS, with deeper penetration of tPA in more permeable clots [23]. Nonetheless, even in EVT studies there are improved functional outcomes with more permeable clots [24].

While many AIS studies on thrombus permeability are based on single phase CTA scans, multiphase or dynamic CTA scans involve serial imaging of the same contrast bolus, and the permeability indices are superior on these scans. Single phase CTA measures thrombus permeability by the increase in Hounsfield units before and after contrast has penetrated into the thrombus. This may underestimate the true permeability if the timing of imaging is suboptimal such as in patients with atrial fibrillation or a poor heart ejection fraction, and if there is a stenosis causing slow contrast flow or if there is a pseudo-occlusion due to a column of static blood [25, 26]. Multiphase CTA has the potential to accommodate these limitations and furthermore measures the dynamic ability of the thrombus to soak up the contrast between phases [27]. Multiphase CT can also accurately determine the thrombus length when the distal end may be demarcated by retrograde contrast from leptomeningeal collateral pathways. This can be useful for optimal EVT device selection and stent retriever deployment [27].

Dense Vessel Sign and Calcified Thrombus

In clots extracted during EVT, histological analysis typically reveals either red blood cell predominant or fibrin/platelets predominant clots. The density on CT may reflect these constituents, with red blood cells (RBC) increasing the attenuation and a hyperdense artery sign seen in RBC-predominant thrombi rather than fibrin-rich thrombi. In several studies, successful recanalization was achieved more frequently in higher thrombus density (higher Hounsfield Units [HU]) than those of lower HU, after IV tPA or endovascular treatment [28–30]; however, other studies conversely found that a hyperdense MCA sign on pretreatment CT does not affect the treatment outcomes after EVT in acute MCA occlusions [5, 31, 32]. Nonetheless, the hyperdense vessel sign has some usability in predicting the underlying stroke etiology before mechanical thrombectomy, with an underlying intracranial atherosclerotic steno-

sis more frequently found in patients with a negative hyperdense vessel sign than those with a positive sign. Pre-procedural prediction of an underlying vessel stenosis can help the interventionist to refrain from multiple thrombectomy attempts and consider earlier rescue strategies, such as angioplasty or intracranial stenting. The susceptibility weighted imaging (SWI) sequence on the MRI can also be a surrogate marker to detect an RBC-predominant clot, in addition the shape of the SWI clot affects the ease of thrombectomy and angulated or bifurcating clots have worse recanalization [33].

A third rarer type of clot contains calcifications, with an incidence of about 2–3% of embolic ischemic stroke [34–36]. These calcified clots contain high amounts of calcium phosphate and are easily identified by their much higher Hounsfield unit value (approximately 160HU and above) compared to the usual thrombi (which are 50–70HU) [37]. These calcified cerebral emboli are typically tiny and easily missed or mistaken for vessel wall calcification. They can be differentiated from vessel wall calcifications, which tend to be linear, by their more roundish shape [34]. In some series one quarter of calcified clots were missed on the initial reading [35, 36].

Identifying calcified clots on the pretreatment CT has implications for the EVT procedure. Calcified thrombi tend to be stiffer and less easily indented and therefore are associated with poorer recanalization rates [37]. While there are only a few small AIS EVT series with calcified emboli, direct aspiration as a treatment modality appears less effective in extraction of these thrombi while stent retriever treatment appears to be little better, although both treatment modalities report a high mortality rate [38, 39]. These calcified cerebral emboli typically arise from the aortic arch, aortic valves of the heart or atherosclerotic plaques near the carotid bifurcation [42]. Identification of the underlying

etiology of calcified clots are clinically important as there are high recurrence rates of up to 43% [35].

Middle Cerebral Artery (MCA) Characteristics and Detecting Underlying Intracranial Stenosis

MCA Tortuosity and Hemorrhagic Complications

Certain imaging parameters at the time of thrombectomy can be associated with an increased risk of intracranial hemorrhage. Shirakawa et al. reported a significant association between the tortuosity of the middle cerebral artery (MCA) and postoperative hemorrhage [40]. They postulated that during stent retriever withdrawal, the proximal MCA segment can be pulled downward and straightened and this displacement of the vessel could damage it or avulse adjacent perforators, which in turn results in subarachnoid hemorrhage. In their study, the MCA tortuosity was evaluated via anteroposterior view images with the supraorbital margin aligned with the anterior cranial base. The distance between the top and bottom of the MCA M1 segment (top-to-bottom, TB distance) was measured with a guidewire in the vessel to maximize visibility. (Fig. 4) The TB distance was significantly more in the group with intracranial hemorrhage than in the nonhemorrhagic group, with multivariate analysis showing a TB distance of >8.8mm as an independent predictor of postoperative hemorrhage (OR 4.85; $P=0.001$). The rate of hemorrhage was also numerically (but not significantly) lower in the aspiration catheter group (20%) than in the stent retriever-only group (45.5%) and in the group using both devices (27.5%), suggesting that using a stent retriever in tortuous MCA vessels increases the rate of hemorrhage. As TB distance can be measured eas-

Fig. 4 Top-to-bottom distance (TB distance) of the first segment of middle cerebral artery seen on coronal view of CT angiogram and digital subtraction angiography (*arrow*)



ily and quickly before thrombectomy, this can potentially reduce the risk of hemorrhagic complications, or at least prompt greater care during the retraction of the device during thrombectomy. Finally, an intermediate catheter can be used to change the angle of force during withdrawal of the stent retriever and align it linear to the vessel, this will reduce the risk of displacing and avulsing adjacent perforators [41].

Truncal vs. Embolic Occlusions

The underlying stroke pathomechanism is a major factor for successful EVT. Thrombi with embolic origin have a higher rate of reperfusion compared to underlying intracranial atherosclerotic stenosis (ICAS), and this applies to both stent retriever and direct aspiration EVT techniques. Thrombi with embolic sources can come from the heart or from a vessel-to-vessel origin such as a stenosing carotid plaque or a symptomatic non-stenosing carotid disease (SyNC) [42]. In Asian populations, converse to Caucasian populations, the major cause of stroke is ICAS, and the prevalence can be up to 20% of AIS [43–46]. Being able to differentiate ICAS from a cardioembolic or SyNC clot is important as reocclusion often quickly occurs in ICAS due to subsequent platelet aggregation, in fact this is one of the ways of diagnosing ICAS during a thrombectomy [47, 48].

A large series of AIS LVO Korean patients were evaluated with CTA to determine the underlying occlusion type. In this study, they dichotomized the occlusion type into more ICAS or truncal type, whereby the distal vessel bifurcation was visible past the occlusion, and a more cardioembolic or branching type: where the bifurcation was not visible (Fig. 5). After a complete stroke work-up was performed, embolic sources were only found in 7% of truncal type occlusions but in 93% of branching type occlusions [49]. This method was able to determine the underlying etiology using the CTA and both a stent retriever and in-

termediate catheter were suggested to be used for truncal occlusions likely to be ICAS, with a low threshold for early rescue stenting. When compared to the presence of atrial fibrillation or the hyperdense artery sign, this truncal vs. embolic sign had a better ROC curve value for predicting stent retriever recanalization. Finally, a truncal type LVO showed a trend to benefit for intra-arterial infusion of glycoprotein IIb/IIIa blocker after rapid reocclusion of the recanalized artery. The authors hypothesized that in truncal lesions, earlier glycoprotein IIb/IIIa blocker or rescue stenting with or without angioplasty can also be considered in such patients [50]. This truncal vs. embolic imaging technique could also be used with digital subtraction angiography (DSA) to detect underlying ICAS; however, in 4% of patients, DSA could not visualize the distal end of the clot because of poor flow through the deployed stent or poorly developed collaterals. Furthermore, using this method with CTA is useful in planning the procedure, whereas DSA information could only be obtained during the EVT itself.

Baseline Volume of Infarct and Penumbra

The Alberta Stroke Program Early CT Score (ASPECTS) scale uses a 10-point ordinal score for the MCA region to estimate the degree of infarction, one point is subtracted for each affected region and a score of 7 or less is considered a larger stroke [51]. Despite the successful application of ASPECTS in clinical trials, the problem with the ASPECTS score is the interobserver variability which exists even for experienced radiologists and neurologist [52–54]. To counter this variability there have been several attempts to harness artificial intelligence to objectively measure this score in the form of e-ASPECTS to ensure speed and reproducibility [55]. In a study of 220 patients, e-ASPECTS score on NCCT had a significant correlation with 3-month clinical outcomes whereas 2 out of 3 expert readers did

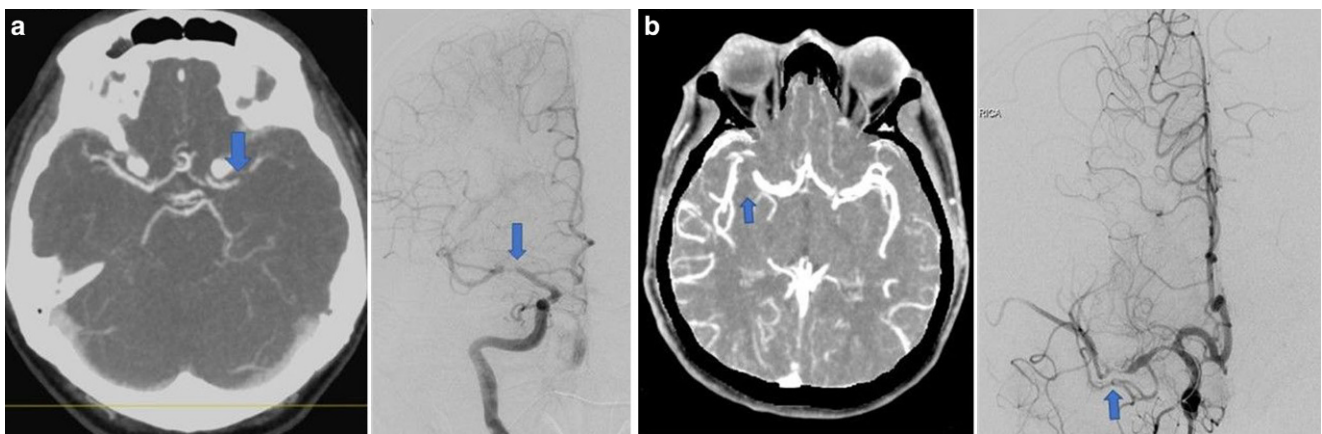


Fig. 5 **a** Truncal type occlusion seen on CT angiogram and digital subtraction angiography, where the bifurcation is visible beyond the occluded segment (*arrow*). **b** “Branching” or Embolic type occlusion seen on CT angiogram and digital subtraction angiography (*arrow*)

not. AI associated imaging interpretation is further supported by a recent meta-analysis of 802 patients with machine learning using a combination of clinical marker and the ASPECTS score, which showed a high accuracy for predicting 3-month functional outcomes of 0.846 (95% CI 0.686–0.902) in patients undergoing thrombectomy [56].

While the ASPECTS score was initially used in CT scans, it has also been used in DWI-MRI sequences for evaluating the ischemic core [57, 58]. The DWI volume of the pretreatment MRI may be used to stratify patients for EVT. Clinical trials have suggested that an DWI volume of 70 ml or more is associated with poor outcomes regardless of treatment, and DWI volumes of 50 ml or less tend to have better functional outcomes with thrombectomy, even in later time windows [59]. More recently, the difference between the DWI volume and the Fluid Attenuated Inversion Recovery (FLAIR) volume, termed DWI-FLAIR mismatch, has been shown to be associated with better recanalization and better functional outcomes [60, 61]. In a large cohort of 1142 stroke patients, the DWI-FLAIR mismatch has also been used to compare patients with unknown onset of strokes against known onset within 6 h. [62] The favorable outcomes of these patients were similar in both arms when they had a DWI-FLAIR mismatch and were treated with thrombectomy (45.2% vs. 53.9%, adjusted relative risk 0.91; 95% CI 0.80–1.04; $P=0.17$).

Perfusion studies can determine the ischemic core and penumbra. There are several different software packages to evaluate perfusion images (RAPID, OLEA, Mlstar, Viz.ai etc), and most software uses a 70% reduction in relative CBF compared with the normal contralateral side (rCBF) to calculate the ischemic core [63]. Recent studies have suggested that rCBF between 30% and 45% of the contralateral region can be used to determine the ischemic core, with more studies choosing 30%. The RAPID CTP algorithm showed that a rCBF threshold $<30\%$ is more specific than rCBF $<38\%$ for predicting DWI final infarct [64]. Other programs use an ipsilateral CBV <1.8 ml/100 g an absolute CBF <15 ml/100 g/min or an absolute Tmax >10 s to estimate the core infarct [63–65]. In these studies, the ischemic penumbra or salvageable area can be determined by the time to maximum intensity (Tmax) with Tmax of 6 $>$ s as a determinant of critical hypoperfusion which will progress into infarction [63, 66]. Typically, a ratio of penumbra to infarct core of 1.8 or more is sufficient for thrombectomy.

One advantage of MRI over CT perfusion is the ability to accurately estimate the ischemic core with DWI, so perfusion MRI is used only to estimate the penumbra, often by using Tmax >6 s [67]. In CT-perfusion, the ischemic core and penumbra is actually a relative comparison, and sometimes the results can be indeterminate or difficult to interpret especially in the ultra-early period [68–71]. Nonetheless, MRIs are less commonly available and unless optimized,

the delayed workflow and longer acquisition time render CT more widely used. Finally, it should be said that DWI lesions can be reversible, especially with faster revascularization and complete reperfusion; furthermore, a DWI volume of 70 ml for a 30-year-old patient would result in a different outcome for a 70-year-old patient [72]. Individualized management for patients with acute stroke is paramount.

Collateral Scoring

In a secondary analysis from the Multicenter Randomized Clinical Trial of Endovascular Treatment for Acute Ischemic Stroke in the Netherlands (MR CLEAN) trial [73] and in the Endovascular Treatment for Small Core and Proximal Occlusion Ischemic Stroke (ESCAPE) trial [74], the collateral status was considered when selecting patients for thrombectomy. They showed that good functional outcomes are associated with better collaterals.

The collateral status can be determined on CT-angiography, with the most common scoring systems being the Tan and Maas grades [75], whereby leptomeningeal collaterals seen in more than 50% of the affected area is considered good. While the prognostic importance of collateral assessment with CT angiography has been established, consensus is lacking on the optimal technique, number of phases and grading systems. Multiphase CTA (mCTA) is a time-resolved CTA in which an arterial and 2 or more venous phases are acquired. With the benefit of the added dimension of time, mCTA allows for visualizing not only the extent but also the filling in and washing out of the collateral vessels as well as improved detection of LVO [76, 77]. The most commonly used multiphase scoring system is from Calgary and has 5 grades of collaterals, with grades 4 and 5 being good collateral status. Clot length is easier to measure with mCTA than sCTA [78] and clot length can be used to predict the effectiveness of IV tPA and to select the length of the stent retriever for EVT. In several studies, mCTA offers advantages over single-phase CTA (sCTA) by better depiction of the tissue at risk, higher interrater reliability, and improved characterization of collateral status. The mCTA has also been validated to be a better predictor of functional outcomes than sCTA for acute stroke, [79] and a recent study showed that this holds true even in the later time window of 5–15 h after the onset of stroke [80]. Contrast-enhanced MR angiography is comparable with CT angiography for collateral assessment [81, 82]; however, the flow-related signal in time-of-flight MR angiography is mainly via antegrade flow and provides poor information about the collateral flow [74].

Even in the most streamlined MRI stroke protocols, gradient echo or SWI is performed to rule out intracra-

nial bleeds. During these sequences, the presence of deep medullary veins can sometimes be visible on the ipsilateral side of ischemic stroke. The asymmetrical presence of such veins has been associated with poorer functional outcomes on ordinal shift analysis (OR 3.19, 95% CI: 1.24–8.21, $P=0.016$) and can add predictive value to the initial NIHSS [83]. This is a fast and easy radiological parameter that can be used to prognosticate MCA AIS patients.

In centers which do perfusion imaging, the collateral status can also be inferred from perfusion imaging. The relative CBV (rCBV) of the ipsilateral compared to the contralateral normally perfused area, has been shown to correlate with the angiographic collateral status [84]. A more accurate scoring system is the perfusion collateral index where the rCBV is multiplied by the volume of tissue with moderate hypoperfusion, defined by a TMax of 2–6 s. [85].

Another parameter which can be derived from perfusion scans is the hypoperfusion intensity ratio (HIR), which is the volumetric ratio of tissue with a Tmax > 10 s and Tmax > 6 s [86]. HIR is associated with collateral status and the speed of infarct growth [87]. A HIR of 0.5 is the threshold of determining infarct core growth versus core stability, above which patients are considered fast progressors. A HIR of 0.4 or less has been deemed to be more suitable for thrombectomy in AIS patients as they are considered slow progressors [87].

In patients who present at a later time window, up to 24 h after the onset of stroke, perfusion imaging is crucial to rule out patients who are unsuitable for treatment and this too has become the standard of care worldwide [59, 88].

Conclusion

There are several signs on pretreatment CT or MRI which have been shown to be associated with improved recanalization, functional outcomes, and mortality. The interventionist should be familiar with the underlying evidence to be able to make time-sensitive decisions in an acute stroke situation.

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Declarations

Conflict of interest T. Andersson is a consultant for Neuravi/Cerenovus, Anaconda, Amnis Therapeutics, and Rapid Medical; served on the

steering committees of the ARISE studies. P. Bhogal reports personal fees from phenox, personal fees from perflow, and grants and personal fees from Balt outside the submitted work; in addition, P. Bhogal has a patent for a Vasospasm stent issued. M. Jing, J.Y. Yeo, S. Holmin, F. Arnberg, C. Yang, A. Gopinathan, T.M. Tu, B.Y.Q. Tan, C.H. Sia, H.L. Teoh, P.R. Paliwal, B.P.L. Chan, V. Sharma and L.L. Yeo declare that they have no competing interests.

Ethical standards For this article no studies with human participants or animals were performed by any of the authors. All studies performed were in accordance with the ethical standards indicated in each case.

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