Current and novel non-invasive imaging modalities in vascular neurosurgical practice

Abstract

Radiological investigations are a powerful tool in the assessment of patients with intracranial vascular anomalies. 'Visual' assessment of neurovascular lesions is central to their diagnosis, monitoring, prognostication and management. Computed tomography and magnetic resonance imaging are the two principal non-invasive imaging modalities used in clinical practice for the assessment of the cerebral vasculature, but these techniques continue to evolve, enabling clinicians to gain greater insights into neurovascular pathology and pathophysiology. This review outlines both established and novel imaging modalities used in modern neurovascular practice and their clinical applications.

Key words: Angiography; Arteriovenous malformation; Computed tomography; Magnetic resonance imaging; Neurosurgery; Neurovascular; Spinal vascular malformation; Subarachnoid haemorrhage

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Introduction

Imaging is an indispensable tool in the assessment of patients with intracranial vascular anomalies. 'Visual' assessment of neurovascular lesions is central to their diagnosis, monitoring, prognostication and management. Since the first X-ray was taken in 1895 (Withers, 1931), imaging techniques have undergone a rapid evolution into the complex modalities available today. Computed tomography and magnetic resonance imaging scans underpin the majority of modern imaging techniques, allowing for the generation of sophisticated images and data. This article describes the applications of imaging in the context of neurovascular pathology and explains how these are used in certain neurovascular conditions (Table 1).

Computed tomography techniques

Computed tomography is one of the most widely used imaging modalities in modern medicine. Computed tomography is a composite of X-rays at multiple levels, used to create a detailed and multi-slice assessment. It is quick, non-invasive and detailed, allowing for rapid and accurate in-vivo visualisation of the human body. Computed tomography allows clinicians to acquire spatial and temporal details of the brain parenchyma, surrounding bone structures and cranial vasculature.

Table 1. Definitions of neurovascular abnormalities addressed in this review

Neurovascular abnormality	Definition
Aneurysmal subarachnoid haemorrhage	Rupture of a cerebral aneurysm leading to bleeding within the subarachnoid space
Intracranial aneurysm	Widening and weakening of the wall of a cerebral artery
Arteriovenous malformation	An abnormal nidus-type connection between arteries and veins
Dural arteriovenous fistula	An abnormal fistula between arteries and veins within the dura

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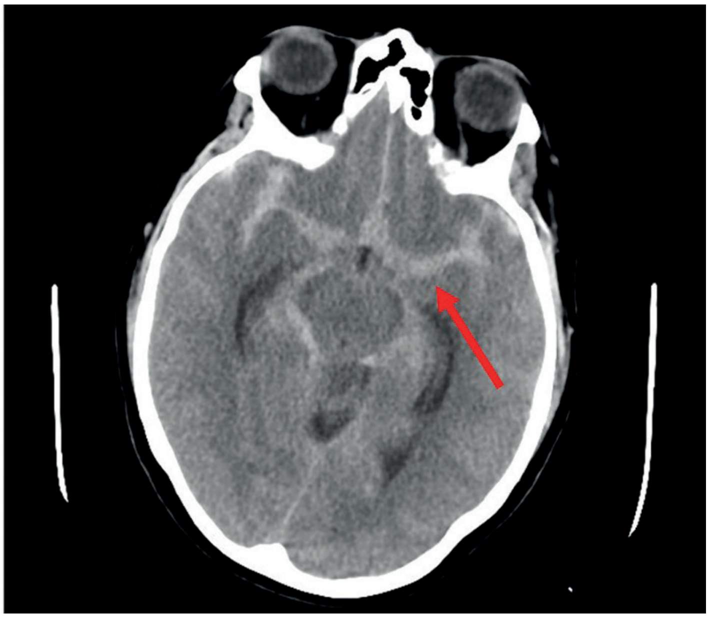

Figure 1. Non-contrast computed tomography head with hyperdensity within the subarachnoid space representing a subarachnoid haemorrhage (arrow).

Table 2. Sensitivity of non-contrast computed tomography head images in the detection of neurovascular pathologies

Application	Sensitivity
Thrombosis	20–75%
Subarachnoid haemorrhage	99% at 6 hours (Heit et al, 2017) 58% at 5 days (Dubosh et al, 2016) 50% at 7 days 0% at 3 weeks
Vasospasm in subarachnoid haemorrhage*	56% (Wintermark et al, 2002)

**Cerebral ischaemic changes on non-contrast computed tomography during diagnosis of delayed cerebral ischaemia attributed to vasospasm in subarachnoid haemorrhage*

Non-contrast computed tomography

Non-contrast computed tomography head images are often the first-line imaging modality in the assessment of a patient with a concerning history. Non-contrast computed tomography head images in the neurovascular patient are sensitive for the detection of acute ischaemic events and intracranial bleeds, including subarachnoid haemorrhage and intraparenchymal bleeds (Heit et al, 2017) (Figure 1).

When assessing intracranial bleeds, the distribution of blood gives information on the potential underlining pathogenesis and location of lesions. However, the sensitivity of non-contrast computed tomography head images in the detection of a subarachnoid haemorrhage decreases as the time from ictus increases, demonstrating almost 100% sensitivity within 6 hours but decreasing to 50% after 7 days (Van Gijn and Van Dongen, 1982; Dubosh et al, 2016) (Table 2). A combination of investigations is advised when a patient's narrative suggests an intracranial bleed and suboptimal imaging is available (Marcolini and Hine, 2019).

Computed tomography angiography

The cerebral arteries can be visualised with computed tomography angiography. The ability of computed tomography angiography to detect an intracranial aneurysm decreases as the size of the aneurysm decreases; the sensitivity for lesions of 10 mm is 100%, but with lesions <3 mm sensitivity is between 83 and 91% (Yang et al, 2017) (Table 3). However,

Table 3. Sensitivity of computed tomography angiography head images in the detection of neurovascular pathologies

Application		Sensitivity
Intracranial aneurysm		Aneurysm >10 mm – 100%
Thrombosis		98%
Arteriovenous malformation		91% overall (Biswas et al, 2015) 100% >3 cm (Sun et al, 2013)
	<3 cm unruptured	87% (McCormack and Hutson, 2010)
	<3 cm ruptured	96%
	Feeding artery aneurysm	90%
	Intranidal aneurysm	83%
Dural arteriovenous fistula		100%
Vasospasm in subarachnoid haemorrhage		64%

the sensitivity increases in ruptured aneurysms (Donmez et al, 2011) (Figures 2 and 3). A study has suggested that 13% of patients with a negative computed tomography angiography were found to have an anomaly on subsequent digital subtraction angiography, suggesting a lower negative predictive value (Heit et al, 2016). The literature suggests a combination of non-contrast computed tomography head and computed tomography angiography may be sufficient to rule out a subarachnoid haemorrhage. In combination, if these two investigations are negative there is a 99.43% probability there will be no aneurysmal subarachnoid haemorrhage (McCormack and Hutson, 2010). The current guidance for the assessment of a probable subarachnoid haemorrhage with a negative non-contrast computed tomography remains to perform a lumbar puncture at least 12 hours post ictus (Arora et al, 2010). Further to this, computed tomography angiography is often used for the diagnosis of large vessel vasospasm to determine amenability to endovascular treatment (Shankar et al, 2012) (Figure 4).

Computed tomography angiography is also useful in the detection of arteriovenous malformations and can detect 90% of arteriovenous malformations (rising to 100% of those >3 cm in size). Computed tomography angiography can demonstrate an arteriovenous malformation-associated aneurysm with a sensitivity of 90% in a feeding artery and 83% in intranidal vessels (Gross et al, 2012).

The computed tomography angiography source data can be viewed in different ways with the use of appropriate software packages. For example computed tomography angiography can be interrogated either as maximum intensity projection or three-dimensional volume rendered images (Figure 3). Considerations before performing computed tomography angiography include the additional radiation dose and the use of contrast medium.

Four-dimensional computed tomography angiography

Four-dimensional computed tomography angiography, also known as time-resolved or dynamic three-dimensional computed tomography angiography, is a technique which allows non-invasive assessment of intracranial vascular flow dynamics over time. Wang et al (2014) found four-dimensional computed tomography angiography to be as accurate as digital subtraction angiography at localising arteriovenous malformations, with the ability to demonstrate the main feeding artery and all draining veins associated with arteriovenous malformations. Four-dimensional computed tomography was able to detect 97% of cranial dural arteriovenous fistulas (Kortman et al, 2015) and was also able to identify retrograde venous flow in cortical veins, a characteristic associated with the increased risk of haemorrhage. In subarachnoid haemorrhage, four-dimensional computed tomography angiography has demonstrated a higher predictive value for haematoma expansion compared to conventional computed tomography angiography because of its temporal nature. This is achieved by detection of the ‘spot sign’ (extravasation of contrast material), which

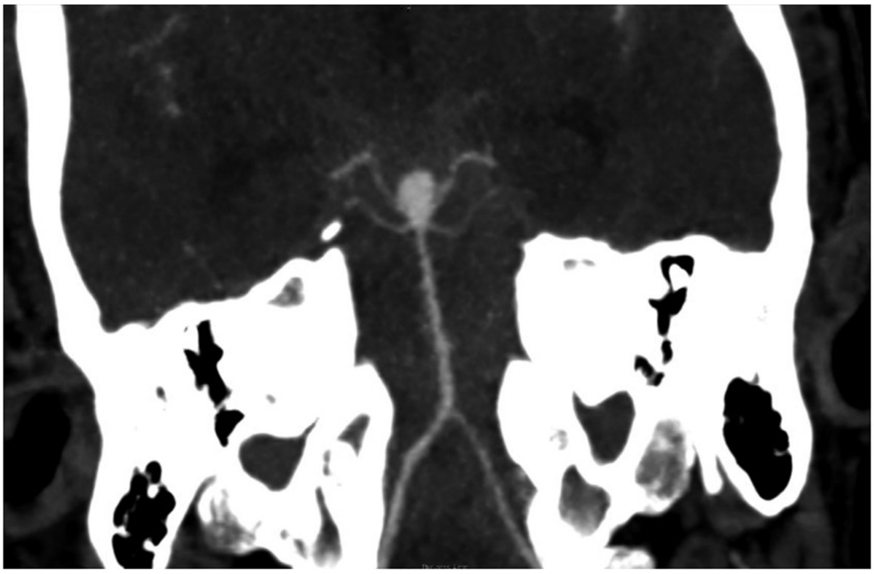

Figure 2. Computed tomography angiography image demonstrating a large 8 mm basilar tip aneurysm.

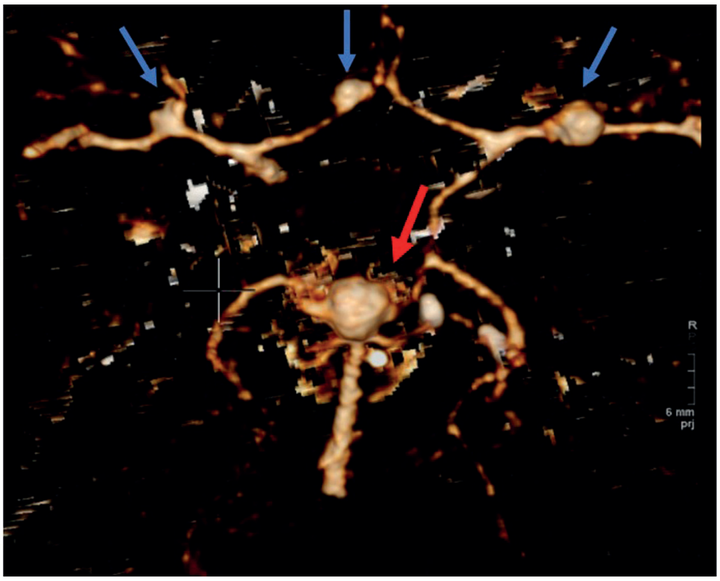

Figure 3. Three-dimensional reconstruction of the computed tomography angiography shown in Figure 2. Basilar tip aneurysm (red arrow) with further aneurysms seen on the left (3 mm) and right (5 mm) middle cerebral arteries and left anterior communicating artery (3 mm) (blue arrows).

is associated with increased mortality (Sun et al, 2013). In summary, four-dimensional computed tomography angiography can not only demonstrate the location of neurovascular abnormality but it can give further information on flow dynamics which are useful prognostic factors, although this further information comes at the cost of an increased radiation dose.

Computed tomography perfusion

Computed tomography perfusion approximates cerebral perfusion using an intravenous contrast agent and is frequently used in the assessment of acute thrombotic stroke. Computed tomography perfusion allows the calculation of values such as cerebral blood volume, cerebral blood flow and mean transit time by measuring the time for contrast medium to reach a certain concentration at cerebral vascular regions of interest. Within infarcted tissue, autoregulation is lost and both cerebral blood volume and mean transit time are reduced; however, in a penumbra, autoregulation is preserved and mean transit time is increased with cerebral blood volume maintained or increased (National Institute for Health and Care

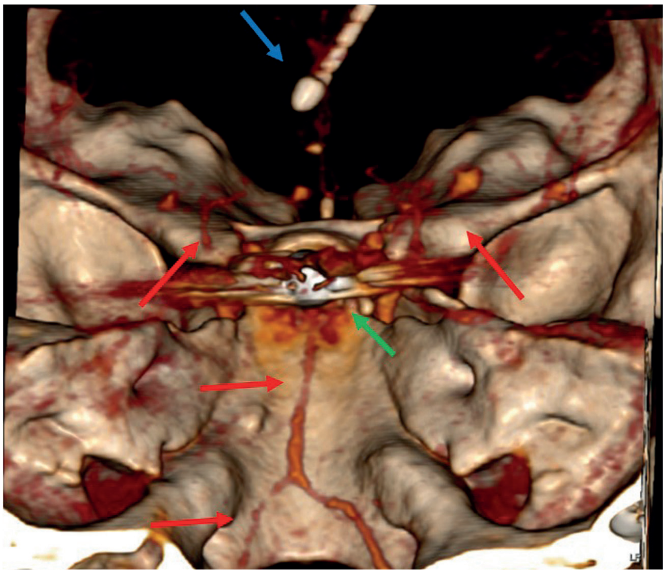

Figure 4. Computed tomography angiography three-dimensional reconstruction from Figures 2 and 3. This image was taken 4 days post-subarachnoid haemorrhage during the assessment of vasospasm. An external ventricular drain can be seen within the ventricles (blue arrow). Coiling artefact is also evident (green arrow). There is an extensive reduction in the diameter of the vessels (red arrows) compared with Figure 3, indicating vasospasm.

Excellence, 2019). This technique is used in the assessment of acute thrombotic stroke to quantify a potential recuperation ratio (Wintermark et al, 2002).

Computed tomography perfusion may be used in the assessment of delayed cerebral ischaemia following aneurysmal subarachnoid haemorrhage. Computed tomography perfusion has superior sensitivity for delayed cerebral ischaemia compared to non-contrast computed tomography and computed tomography angiography (84% vs 56% and 64%) (Dankbaar et al, 2009) (Table 4) and is predictive of permanent neurological deficits and infarctions on subsequent imaging (Dankbaar et al, 2010). A meta-analysis also demonstrated that computed tomography perfusion aids in the radiological diagnosis of delayed cerebral ischaemia and suggests the following criteria: cerebral blood flow of less than 25 ml/100 g/minute and/or a mean transit time of more than 6.5 seconds for the diagnosis of delayed cerebral ischaemia (Cremers et al, 2014). Computed tomography perfusion is also useful in assessing the effect of endovascular angioplasty in vasospasm-induced ischaemia for patients with subarachnoid haemorrhage by measuring restoration of cerebral blood flow and its correlation with clinical improvements post-endovascular treatment. However, computed tomography perfusion is not included in current guidance for the investigation of delayed cerebral ischaemia as further research into its clinical application is needed (Bederson et al, 2009).

Magnetic resonance imaging techniques

Magnetic resonance imaging can produce high tissue resolution images through the application of high strength magnets to achieve high quality assessment (Currie et al, 2013). Improvements in computer software and the fine-tuning of complex algorithms have improved the quality and timing of imaging acquisition.

Table 4. Sensitivity of computed tomography perfusion head images in the detection of neurovascular pathologies

Application	Sensitivity
Thrombosis (Hana et al, 2014)	96% if ischaemic volume >12 cm^2 80% if ischaemic volume 9–12 cm^2
Vasospasm in subarachnoid haemorrhage (Boddu et al, 2014)	84%

Table 5. Sensitivity of magnetic resonance angiography head images in the detection of neurovascular pathologies

Application		Sensitivity
Thrombosis		84%
Intracranial aneurysm	<5 cm	98%
Arteriovenous malformation	>3 cm	100%
	<3 cm – unruptured	71%
	<3 cm – ruptured	74%
Dural arteriovenous fistula		87%

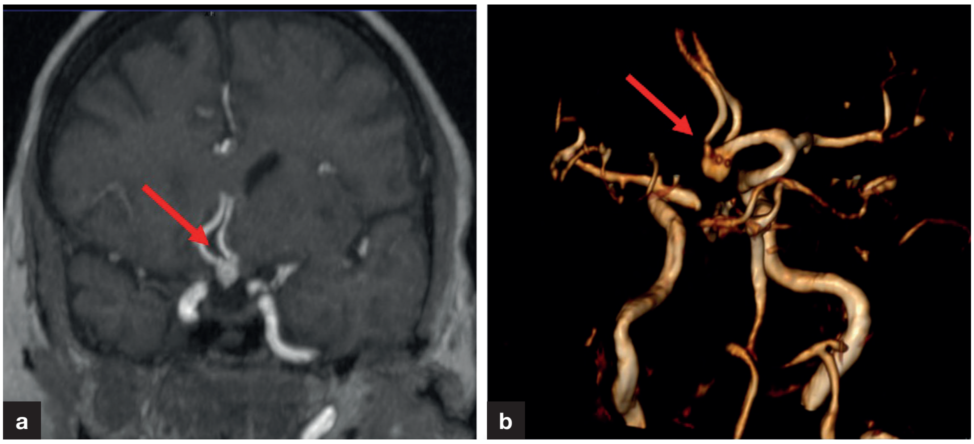

Figure 5. a. Time-of-flight magnetic resonance angiography images with (b) three-dimensional construction from the monitoring of an anterior communicating aneurysm. These images demonstrated a 6 mm right anterior communicating aneurysm (arrows).

Magnetic resonance angiography

Magnetic resonance angiography applies the basic magnetic resonance imaging technique to blood flow within the vessels to obtain volumetric blood flow images. There are several techniques used, including time-of-flight, phase contrast and contrast-enhanced magnetic resonance angiography.

Magnetic resonance angiography is not generally used in an acute setting but is routinely used to monitor unruptured intracranial aneurysms and for follow up of previously treated aneurysms. Magnetic resonance angiography has a sensitivity of 98% and specificity of 95% in the detection of unruptured aneurysms <5 mm in size when compared with digital subtraction angiography (Li et al, 2014) (Table 5). Aneurysmal size and future growth are recognised risk factors for subsequent rupture and therefore regular magnetic resonance angiography is frequently used in the surveillance of patients with unruptured intracranial aneurysms (Greving et al, 2014)(Figure 5). Research into the detection of other risk factors, based on flow dynamics and sheer arterial wall stress, has found arterial wall enhancements post ferumoxytol administration may reflect inflammation and wall stress. This can indicate a potentially unstable aneurysm or help to determine the culpable aneurysm in someone presenting with subarachnoid haemorrhage who has multiple intracranial aneurysms (Hasan et al, 2012; Edjlali et al, 2014).

During the follow up of patients with coiled aneurysms, detection of an aneurysmal remnant may warrant additional treatment. Digital subtraction angiography was previously the gold standard follow-up technique in this cohort, but the non-invasive nature of magnetic resonance angiography and its equivalent level of accuracy mean that it has now become the gold standard for post-treatment follow up (Schaafsma et al, 2012). Magnetic resonance angiography is also useful in the follow up of stented cerebral aneurysms (Boddu et al, 2014), but is not routinely used post-clipping because of the artefact produced by the clips.

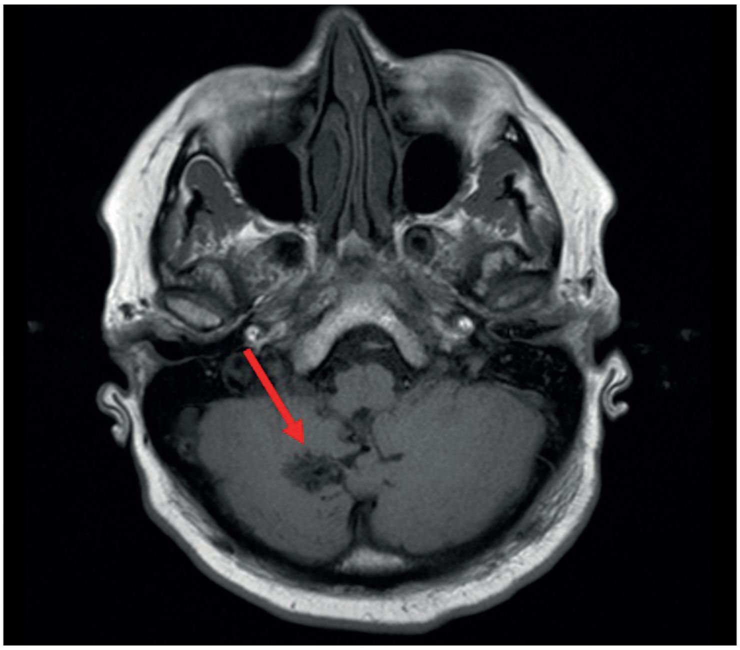

Figure 6. Magnetic resonance angiography T1 axial image demonstrating a nidus within the right cerebellar hemisphere representing an arteriovenous malformation (arrow).

Magnetic resonance angiography is a valuable tool in the assessment of dural arteriovenous fistulas and has found to be 87% sensitive and 100% specific compared to digital subtraction angiography with a low false negative rate (Noguchi et al, 2004; Farb et al, 2009). The same is true for arteriovenous malformations (Saleh et al, 2008), but digital subtraction angiography remains the gold standard for arteriovenous malformation assessment (Figure 6).

Time-resolved contrast-enhanced magnetic resonance angiography

Dynamic or time-resolved contrast-enhanced magnetic resonance angiography, also known as four-dimensional magnetic resonance angiography, is a magnetic resonance angiography technique used in the assessment of spinal vascular malformations. Spinal vascular malformations are often difficult to diagnose on conventional magnetic resonance imaging because of the similar characteristics with other possible pathologies on imaging. Catheter-based digital subtraction angiography is the invasive gold standard for spinal vascular malformation assessment, but refinement of the technique of time-resolved contrast enhanced-magnetic resonance angiography has lead this non-invasive method to prove promising. The acquisition of spatial and temporal information with adequate resolution in time-resolved contrast enhanced-magnetic resonance angiography is a fine balance and was previously difficult to achieve. A time-resolved imaging of contrast kinetics (TRICKS) method uses k-space central regions of interest to acquire focused spatial and temporal information and limits peripheral data to ensure a high resolution is achieved in the regions of interest (Petkova et al, 2009). This technique has allowed for the adequate acquisition of temporal resolution to evaluate the vasculature in several areas of the body. A retrospective comparison of the TRICKS technique and spinal digital subtraction angiography in the evaluation of spinal vascular malformations demonstrated TRICKS to have high sensitivity for spinal vascular malformations and a frequent ability to identify the level of arteriovenous shunting (Amarouche et al, 2015). This study reported time-resolved contrast enhanced-magnetic resonance angiography to have incorrectly assessed spinal vascular malformations in 13% of cases. Overall, it had a sensitivity and specificity of 98% and 63% respectively when compared to spinal digital subtraction angiography. Given the rarity of spinal vascular malformations, there are limited published data, but TRICKS may be advantageous in locating the spinal level of arteriovenous shunting to allow for a more focused spinal digital subtraction angiography approach.

Key points

- The introduction of computed tomography angiography has allowed for rapid assessment of the cerebral vasculature.
- Magnetic resonance imaging has replaced invasive digital subtraction angiography in the follow up for treated and untreated intracranial aneurysms.
- Advancements in magnetic resonance imaging techniques have allowed for spatial and temporal information to further characterise neurovascular lesions.

Conclusions

The mainstream non-invasive imaging modalities currently used in the assessment of the neurovascular neurosurgical patient are based on computed tomography and magnetic resonance imaging. The development of different techniques and post-processing software allow for intricate imagery in a non-invasive manner to improve the assessment, diagnosis, monitoring and management planning of patients with neurovascular pathology.

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Conflicts of interest

The authors declare no conflicts of interest.

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