Noninvasive Imaging Techniques in the Diagnosis and Management of Aneurysmal Subarachnoid Hemorrhage

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KEYWORDS

- Subarachnoid hemorrhage • Vasospasm
- Aneurysmal subarachnoid hemorrhage
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Aneurysmal subarachnoid hemorrhage (aSAH), a devastating medical condition and its accompanying sequelae pose significant diagnostic and therapeutic challenges for the neurosurgeon, interventional neuroradiologist, and neurointensivist. The management of the primary and secondary complications of aSAH requires use of a multimodality approach in many cases, both for the diagnosis of aSAH as well as the radiographic diagnosis and management of vasospasm (VS). Currently, digital subtraction angiography (DSA) is the recognized gold standard for the diagnosis of both aSAH and VS, although it is not universally available. Moreover, it is resource intensive, costly, and has a small but not insignificant risk of neurologic complications, making the consideration of other modalities attractive.[1–5] We will present a review of the current literature

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regarding the use of noninvasive imaging studies to aid in the diagnosis of ruptured intracerebral arterial aneurysms and VS, along with the current published data comparing the gold standard of DSA to these newer modalities.

IMAGING FOR THE DIAGNOSIS OF ANEURYSMAL SUBARACHNOID HEMORRHAGE

The initial diagnosis of aSAH is dependent on using a proper history, physical and neurologic examination, laboratory data, and radiographic studies. In the correct population, brain imaging with computed tomography (CT) and lumbar puncture (LP) are standard of care and commonly used when concern for aSAH exists.[6–8] Once the nontraumatic subarachnoid blood is found, then a combination of CT, magnetic resonance (MR) imaging, and/or conventional angiography are used to identify if it is secondary to a ruptured arterial aneurysm. If an aneurysm is confirmed, these modalities are further helpful in characterizing the nature of the aneurysm, identifying the ruptured aneurysm if multiple lesions are found, and to plan for operative or interventional techniques to secure the ruptured aneurysm.

Non–contrast-enhanced Computed Tomography

Noncontrast head CT plays an important role in the emergency evaluation of patients with acute headaches. Among the many causes of thunderclap headaches, a diagnosis of nontraumatic subarachnoid hemorrhage should be made emergently because of a possibility of an underlying ruptured aneurysm. The sensitivity of noncontrast CT to detect SAH in the acute period is greater than 90%; however, supplementary patient history and cerebrospinal fluid analysis maintains an important role in the diagnosis of SAH.[7–12] This may be especially important in subacute SAH presenting days after the initial symptomatic period, where conventional CT has decreased sensitivity for the detection of subarachnoid blood.[9]

Acute hemorrhage in the subarachnoid space appears as areas of hyperdensity in the basal cisterns, cerebral sulci, and/or the ventricles (**Fig. 1**). Despite its characteristic imaging appearance, a wide range of misdiagnosis rates have been reported in the literature. In a recent study, a misdiagnosis rate of 5% was reported for the CT diagnosis of SAH.[13] When clinical suspicion for aSAH exists, a detailed search pattern for blood should be adopted on CT. Careful attention should be paid to areas where a small amount of blood can be easily overlooked. These areas include posterior aspects of the sylvian fissures, interpeduncular cistern, deep cerebral sulci, occipital horns of the lateral ventricles, and the foramen magnum.

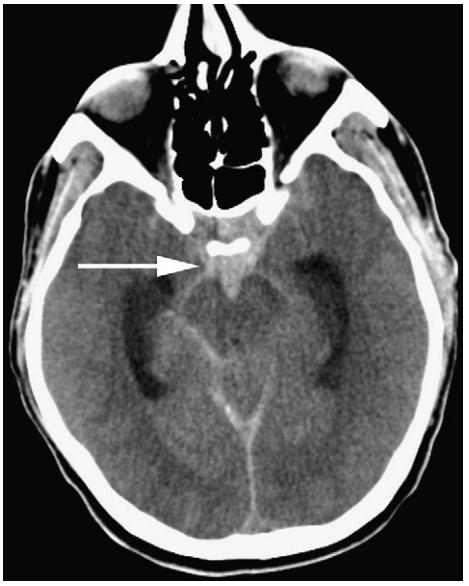

Fig. 1. Axial noncontrast CT image at the level of midbrain shows characteristic appearance of diffuse SAH with arrow pointing to blood collection in interpeduncular cistern suggestive of ruptured basilar tip aneurysm. Please note the early developing hydrocephalus with dilated bilateral temporal horns.

Occasionally, some entities can result in a false positive impression of SAH on CT scans. Crowding of structures at the basal aspect of the brain can create an appearance similar to SAH within the basal cisterns, a term called pseudosubarachnoid hemorrhage. This finding is attributable to elevated intracranial pressure, apposition of pial surfaces, and resultant engorgement of pial veins.[14] Such an imaging appearance can be seen with conditions resulting in diffuse cerebral edema as well as intracranial mass lesions and severe obstructive hydrocephalus (**Fig. 2**). Awareness of this condition, the clinical context, and recognition of diffuse mass effect can help differentiate this entity from ''true SAH.'' Layering of high-density exudates in the subarachnoid space in patients with meningitis as well as prior administration of intravenous contrast for unrelated radiographic examinations may also simulate the imaging features of SAH.[14]

Similar to clinical grading schemes for SAH, imaging-based grading systems have also been proposed. A popular imaging-based grading scheme was proposed by Fisher and colleagues.[15] It is based on the extent and appearance of SAH on CT, and is used to predict the

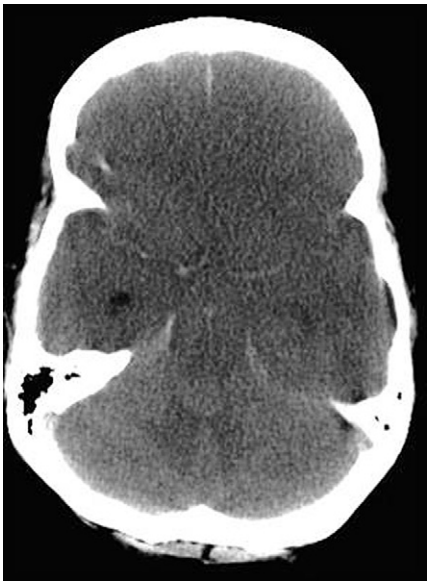

Fig. 2. Noncontrast CT with pseudo SAH due to diffuse severe hypoxia causing apparent hyperdensity in interpeduncular cistern and along the tentorium.

likelihood of developing VS (**Table 1**) and was later revised by Claassen and colleagues (**Table 2**).[16,17] Noncontrast CT can provide information to point toward the location of a ruptured aneurysm, especially important when multiple aneurysms are found to exist. Several studies have confirmed the ability in some cases of CT to predict the location of ruptured aneurysms found later on DSA.[18–22] There are several imaging findings that can help locate the site of ruptured aneurysm. The distribution of blood in the subarachnoid space and thickness of a localized clot can often help with such localization (**Fig. 3**).[14] For example, a large amount of blood along the interhemispheric fissure indicates anterior communicating artery aneurysms. Similarly, a large amount of blood in a sylvian fissure indicates middle cerebral artery aneurysm. Posterior fossa distribution of blood is seen with basilar, superior cerebellar, and posterior inferior cerebellar artery (PICA) aneurysms. On occasion, one may be able to directly observe a ruptured aneurysm as a lucent area within the subarachnoid clot. However, even despite these helpful clues, correct determination of ruptured aneurysm may be difficult or impossible in many cases.

The ability of noncontrast CT to correctly identify the vascular location of aSAH was recently retrospectively studied by Karttunen and colleagues in 180 patients.[22] The entire cohort had a noncontrast CT done within 24 hours of SAH, and DSA was done within 48 hours of SAH. All patients studied had confirmed SAH, and were taken for surgical clipping. Initial noncontrast CT was able to correctly identify the site of aneurysmal rupture in general for middle cerebral artery (MCA) and anterior communicating artery (AcoA) aneurysms, but for aneurysms at other sites, accurate predictions were not possible in this study. The presence of a parenchymal hematoma, seen in 34% of the cohort, was a statistically significant predictor for evaluating the location of the ruptured aneurysm. The amount or distribution of the subarachnoid blood did not correlate well with the location of other aneurysms. A similar-sized retrospective study reported earlier that only anterior cerebral artery (ACA) or AcoA aneurysms were accurately predicted with noncontrast CT, and that MCA, internal carotid artery (ICA), and posterior circulation artery aneurysms were inconsistent or otherwise poorly predicted by noncontrast CT alone.[23] Classically, focal parenchymal hematomas of the skull base, medial temporal lobe, and intraventricular hemorrhage into the third ventricle have been associated with PICA aneurysms, posterior communicating (PCOM) aneurysms, and basilar artery aneurysms respectively.[24]

Perimesencephalic hemorrhage can have imaging appearance that can be confused with aSAH, although certain characteristics may help identify this benign condition. A location centered

Table 1
Fisher grading system

Grade	CT Appearance of Subarachnoid Hemorrhage
1	None evident
2	Less than 1 mm thick
3	More than 1 mm thick
4	Any thickness with associated parenchymal or intraventricular hematoma

Data from Villablanca JP, Martin N, Jahan R, et al. Volume-rendered helical computerized tomography angiography in the detection and characterization of intracranial aneurysms. J Neurosurg 2000;93:254–64.

Table 2
Subarachnoid hemorrhage computed tomography rating scale[16]

Grade	CT Appearance of Subarachnoid Hemorrhage
0	No SAH or IVH
1	Minimal SAH, no IVH in both lateral ventricles
2	Minimal SAH with IVH in both lateral ventricles
3	Thick SAH, no IVH in both lateral ventricles
4	Thick SAH, with IVH in both lateral ventricles

around the anterior aspect of the midbrain, absence of large amounts of intraventricular blood, and potential extension to the posterior intrahemispheric or fissure or basal part of the sylvian fissure are characteristic imaging features of this condition. There is lack of parenchymal hematoma and a four-vessel angiogram is negative for aneurysm (**Fig. 4**)[25,26] (D. Gandhi, personal communication, 2009).

Computed Tomography Angiography

Much enthusiasm exists over the utility of CT angiography (CTA) as a less invasive diagnostic tool in the investigation of SAH found on noncontrast CT or LP. The advantages of CTA include its near uniform availability, safety profile, high spatial resolution, and limited time required to perform the test. Additionally, it can be obtained at the same sitting when the patient makes a trip to the CT scanner for the noncontrast CT. In recent years, multidetector CT (MDCT) technology is gaining popularity and has become widely available. MDCT scanners provide superior image resolution, extended z-axis coverage, and markedly reduced acquisition times. Additionally, with many centers increasingly using endovascular treatments over microsurgical clipping for treatment of aSAH, strain on limited angiographic resources for diagnostic purposes has increased.[1,27] It is hoped that diagnostic CTA may help offset some of the strain on this resource and increase use for therapeutic purposes.[28]

Several other advantages of the use of CTA in the setting of SAH that should be emphasized include its ability to demonstrate the precise relationship between bony structures of the skull and the aneurysm. Additionally, the relationship of the aneurysm to the brain structures and/or the hematoma can be studied, which is useful information for treatment planning, especially when craniotomy is being considered. The CTA may also help demonstrate other characteristics of the aneurysm that are less well studied on the DSA; for example, presence of endo-luminal thrombus as well as calcification of the aneurysm wall. Preoperative knowledge of these aneurysm characteristics significantly aids in therapeutic decisions (**Figs. 5** and **6**).

Published reports of the sensitivity and specificity of CTA are encouraging its increasingly widespread use as a sole imaging modality for surgical or endovascular treatment planning of aSAH.[6,29–31] Wintermark and colleagues[31] published a report of the comparison of multislice CTA with DSA for 50 patients with aSAH. The sensitivity was 94.8% and the specificity was 95.2% for the detection on a per aneurysm basis and 99.0% and 95.2% on a per patient basis, respectively. In this study, a cut-off size of 2 mm was found as the inflection point in which multislice CTA became less able to detect intracerebral aneurysms, a finding that has since been replicated.[32,33] This is important, given that the slight majority of aneurysms implicated in SAH are 5 mm or smaller as reported in the International Subarachnoid Aneurysm Trial (ISAT) of more than 2000 patients.[34] Other studies have published sensitivities for the detection of aneurysms 5 to 12 mm in size of 90.6% and 100.0% for aneurysms larger than 12 mm.[35] This article showed a concerning low sensitivity at 83.3% for aneurysms smaller than 5 mm.[35] The overall sensitivity was reported at 89.5% compared with DSA. If the history and examination findings yield a high pretest probability of aSAH and the CTA fails to show an aneurysm, follow-up studies including DSA should be done.[1] Given this understanding, it may be reasonable to use CTA as the initial test for characterizing aSAH, with the understanding that a negative CTA in the setting of SAH is of very limited use.

The dose of intravenous contrast given during CTA is roughly 80 to 100 mL for many protocols[1] and compares very favorably when compared with a four-vessel DSA study. The radiation dose in CTA (100 mGy) has been estimated to be less than that of DSA.[1,36] The radiation from CT perfusion (CTP), if needed, adds in the range of 700 to 1400 mGy.[37] There have been reported cases of transient bandage-shaped hair loss after multiple

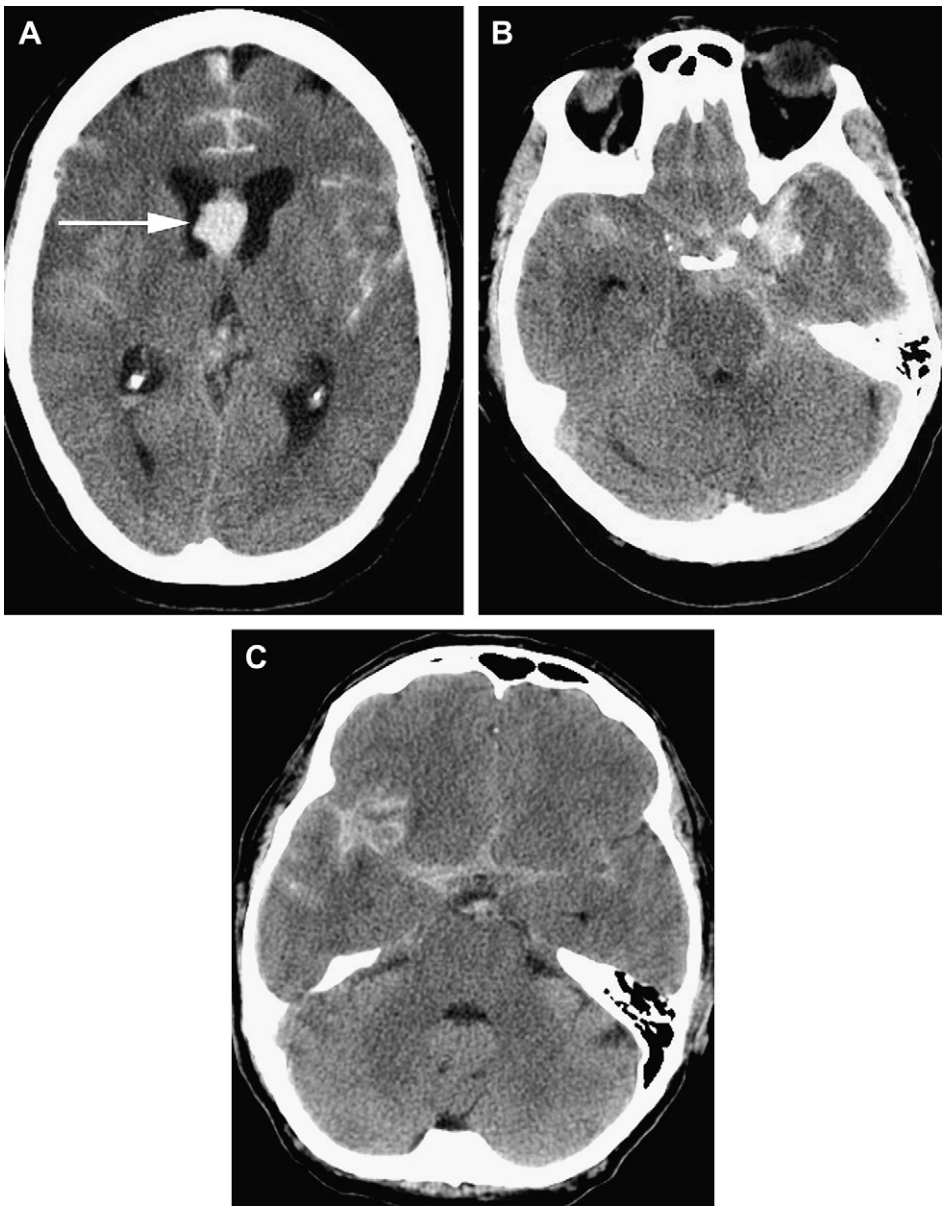

Fig. 3. Noncontrast CT images from different patients demonstrating that particular location of thick clot can often help in predicting the location of ruptured aneurysm: (*A*) Blood collection along interhemispheric fissure from ruptured ACOM aneurysm. (*B*) Focal collection along left side of suprasellar cistern from ruptured left PCOM aneurysm. (*C*) Blood pooling in right sylvian fissure from ruptured middle cerebral artery aneurysm. Please note the lucent center representing the actual aneurysm.

studies of perfusion CT combined with DSA or interventional procedures in a relatively short period of time. In these cases, the overall dose was estimated to be about 3 to 5 Gy to the skin.[38] The danger of excessive radiation exposure must be considered when patients are subjected to combination and repeated studies. There are many strategies available to reduce the radiation dose associated with CT and CTA protocols. Some of these involve changes in the acquisition parameters such as kVp, gantry rotation time, milliampere, and pitch. These changes, however, are a compromise between image quality and radiation dose but can be optimized for desired information from the study and associated noise level that is acceptable for diagnostic purpose. More recent dose-reduction tools include dose modulation, in which the tube current is adjusted along

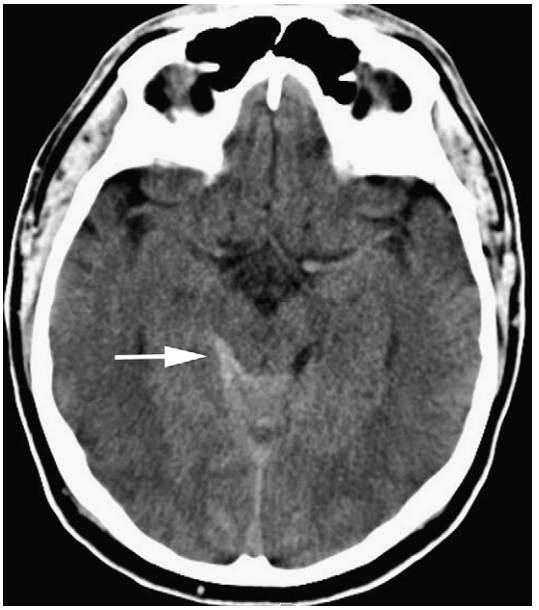

Fig. 4. Perimesencephalic SAH (*arrow*) along right side with no associated parenchymal hematoma. Subsequent DSA was negative for aneurysm.

with the image acquisition, according to patient's size and attenuation. This technique is capable of up to 60% dose reduction without significant image compromise.[36]

Despite the many advantages of CTA and rapid improvement in its quality, DSA is still considered the gold standard for evaluation of SAH. As discussed earlier, CTA has lower sensitivity for the detection of very small aneurysms. Additionally, normal variants like infundibular enlargements and tortuous vascular loops can be mistaken for intracranial aneurysm, resulting in a false positive CTA examination (**Fig. 7**). Therefore, if there is any doubt regarding the findings on CTA, one should have a low threshold for recommending further evaluation with a DSA. Several authors have identified clinical situations where CTA and DSA should be performed in concert, or perhaps DSA should be performed alone. This includes cases where bypass surgery may be required for large aneurysms, aneurysms with complex morphology, and cases where confirmation of the degree of development of the vein of Labbé is needed.[29,30,39–41] Additional concern exists over the concordance of arteriovenous malformation (AVM) and arterial aneurysms, owing to the failure of CTA to demonstrate an AVM in some series.[42] CTA used alone could potentially lead to an incomplete understanding of the vascular anatomy and poor surgical or endovascular planning in these cases.

Magnetic Resonance Imaging

The use of MRI to diagnose SAH and characterize aSAH has been partially limited to an ancillary use as a means to rule out other potential causes of SAH such as venous thrombosis or vasculitis.[43] The sensitivity of T2-weighted gradient echo (GRE) and fluid-attenuated inversion recovery (FLAIR) sequences is thought to increase over time, rather than decrease, as it does for CT.[44,45] In a study of MRI obtained in acute (<4 days from hemorrhage) versus subacute (4–14 days from hemorrhage) SAH, the sensitivity of T2-weighted GRE was 94% and 100%, respectively. FLAIR performed only slightly worse than GRE for the detection of acute or subacute SAH. More recently, available susceptibility weighted imaging (SWI) has the potential to further increase sensitivity for detecting hemorrhage over that of GRE. Nonetheless, MRI has a limited role in the initial or emergency department management of SAH because of logistics and time acquisition issues, although its sensitivity in the setting of acute evaluation of SAH has been further studied.[44–49] Fiebach and colleagues[44] published pilot data from a small series of patients who had a stroke protocol-based 8-minute MRI with 100% sensitivity of detecting SAH on proton density–weighted images. Diffusion-weighted imaging was also positive in 80% of the patients, and perfusion maps were normal in all patients.

Similarly, in a recent study by Yuan and colleagues,[9] similar MRI sequences were studied and compared with the sensitivity of CT and MR in acute (<5 days) and subacute (6–30 days) SAH. In the acute period, SAH was identified on FLAIR in 100% of cases, and on T2-weighted GRE sequences and noncontrast CT both in 90.9% of cases (**Fig. 8**). In the subacute period, FLAIR sensitivity was markedly reduced to 33%, whereas T2-weighted GRE was 100% sensitive and noncontrast CT found SAH in 45.5%. It appears that MRI may be of use in confirming suspected SAH, perhaps when other testing is unavailable or equivocal, or in the subacute phase as a supplement to CT when the sensitivity of CT is markedly reduced.

Magnetic Resonance Angiography

The use of 3D time-of-flight (TOF) magnetic resonance angiography (MRA) as a sole modality for diagnosis and characterization of cerebral aneurysms has been studied. In a large study of 205 consecutive patients with aSAH, a protocol using a 20-minute MRA during the acute period after SAH showed that the lesion could be identified and successful surgical planning undertaken

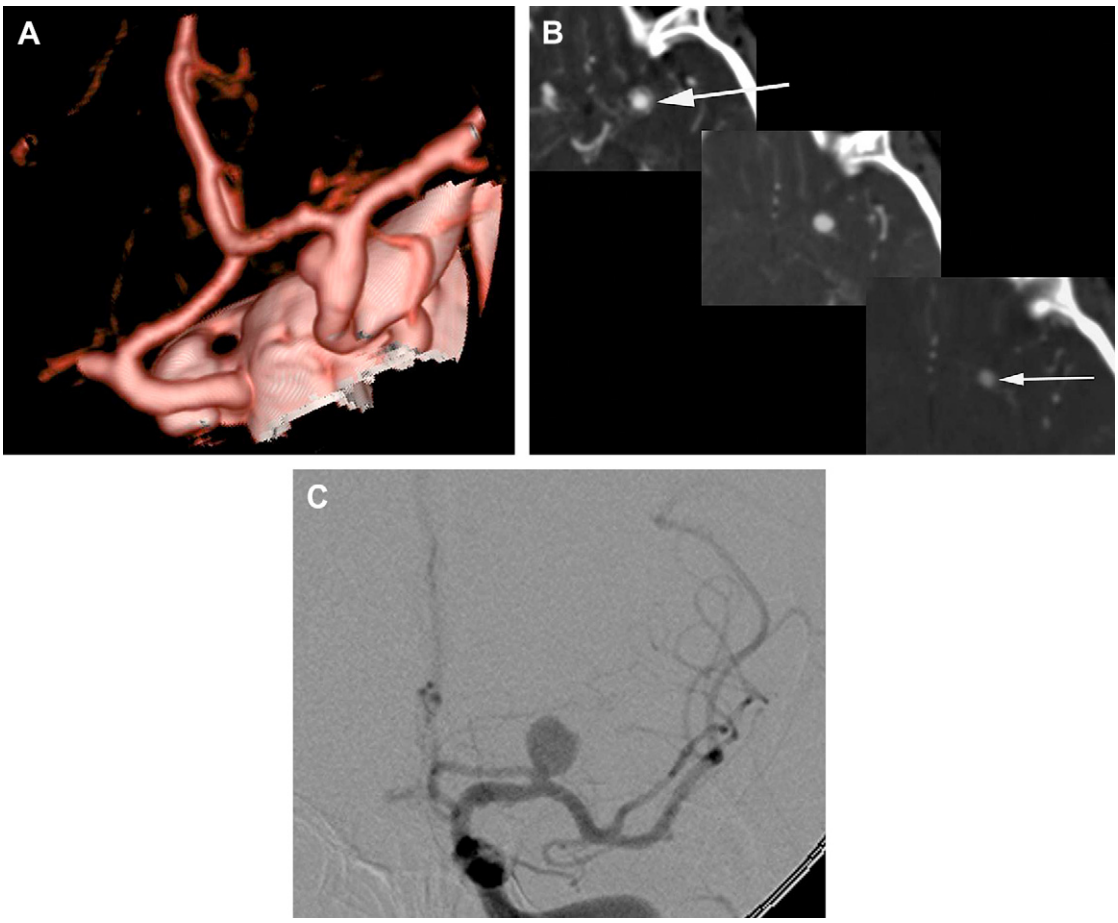

Fig. 5. (*A*) Reconstruction 3D CTA image showing precise location of aneurysm that is distal in relation to the anterior clinoid process, extremely useful information for surgical planning. (*B*) Axial source images from CTA showing thick rim of calcification around the base of contrast-filled aneurysm (*thick arrow*), which is not apparent and can be completely missed on subsequent DSA (*C*) of the same patient.

based on MRA, if the lesion was well characterized by this modality.[50] If an aneurysm was not identified, then DSA was done. One of the 205 patients studied had a false positive result, where a tortuous loop of the MCA was found at craniotomy. In a subset of approximately 16% of these patients, DSA was performed because of inconclusive findings on MRA. Seven asymptomatic aneurysms were found on MRA, all smaller than 5 mm in diameter. Importantly, the neuroradiologists interpreting the MRA data were not blinded to results of the initial noncontrast CT and thus were aided by noting a potential region of interest for the MR study. The authors concluded that DSA could be replaced by 3-dimensional (3D) TOF MRA as the initial diagnostic study in suspected aSAH.

Similar conclusions were made by Sato and colleagues[51] in a study of 108 patients with 3D TOF MRA. This article included both patients with ruptured aSAH and unruptured aneurysms. They concluded that MRA was accurate and useful as the primary imaging modality for the diagnosis of anterior circulation aneurysms of 5 mm diameter or larger. Interestingly, the authors also reported success with surgical planning and intervention without DSA.[51] In a systematic review, White and colleagues[52] reported a sensitivity of MRA in the detection of aneurysms 3 mm or larger of 90%, but this number fell precipitously for smaller aneurysms to a reported sensitivity of less than 40%. Logistics, image degradation as a result of patient movement, sedation issues inherent to MRI/A, and problems for use in high-grade patients make MRA impractical for many acutely neurologically ill patients with acute SAH. It remains unclear at this time whether further advances that may overcome these issues will

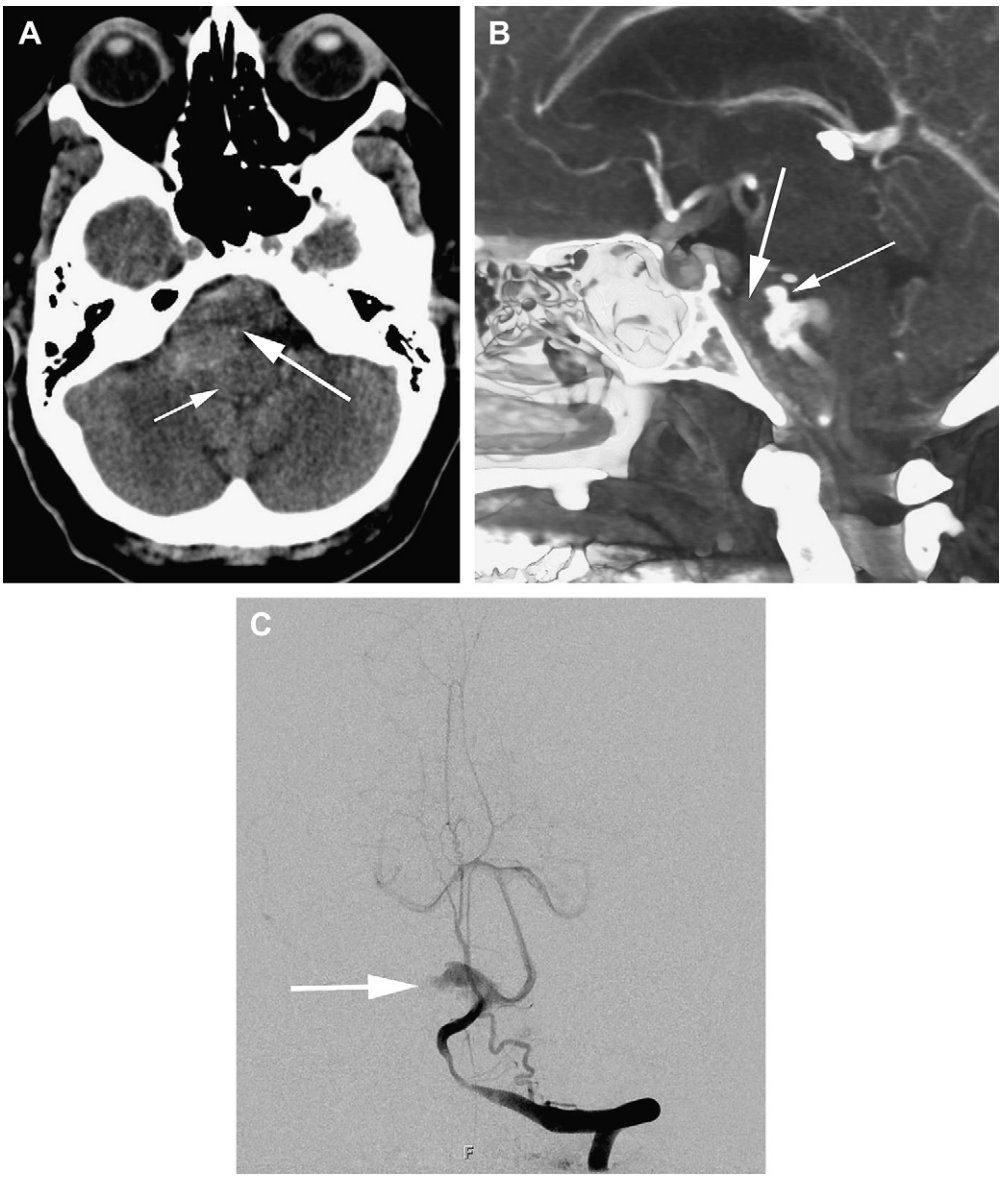

Fig. 6. (*A*) Large hyperdense mass (*large arrow*) located anterior to brainstem (*small arrow*) on this noncontrast CT is suggestive of thrombosed aneurysm. (*B*) Sagittal reformat image from CTA very nicely shows small patent portion of aneurysm filled with contrast (*small arrow*) and the larger thrombosed portion (*large arrow*) of aneurysm. (*C*) DSA also demonstrates the patent portion of the aneurysm (*arrow*) but completely fails to show the true configuration and size of the aneurysm. This important information is best provided by CTA and is critical for treatment planning.

make use of this helpful diagnostic tool more clinically relevant and widespread.[48,49]

IMAGING FOR DIAGNOSIS OF VASOSPASM AFTER ANEURYSMAL SUBARACHNOID HEMORRHAGE

Vasospasm refers to the diminution in cerebral blood flow seen after aneurysmal SAH owing to the decreased caliber of intracranial arteries.[53,54] This was originally described by Ecker and Riewmanschneider,[55] and has since been the subject of much laboratory research and clinical investigation. Other terminology used includes VS seen only on DSA or CTA referred to as ''angiographic vasospasm.'' Also used are the terms ''delayed ischemic deficit'' or ''clinical vasospasm,'' and thus refer to VS that has become clinically

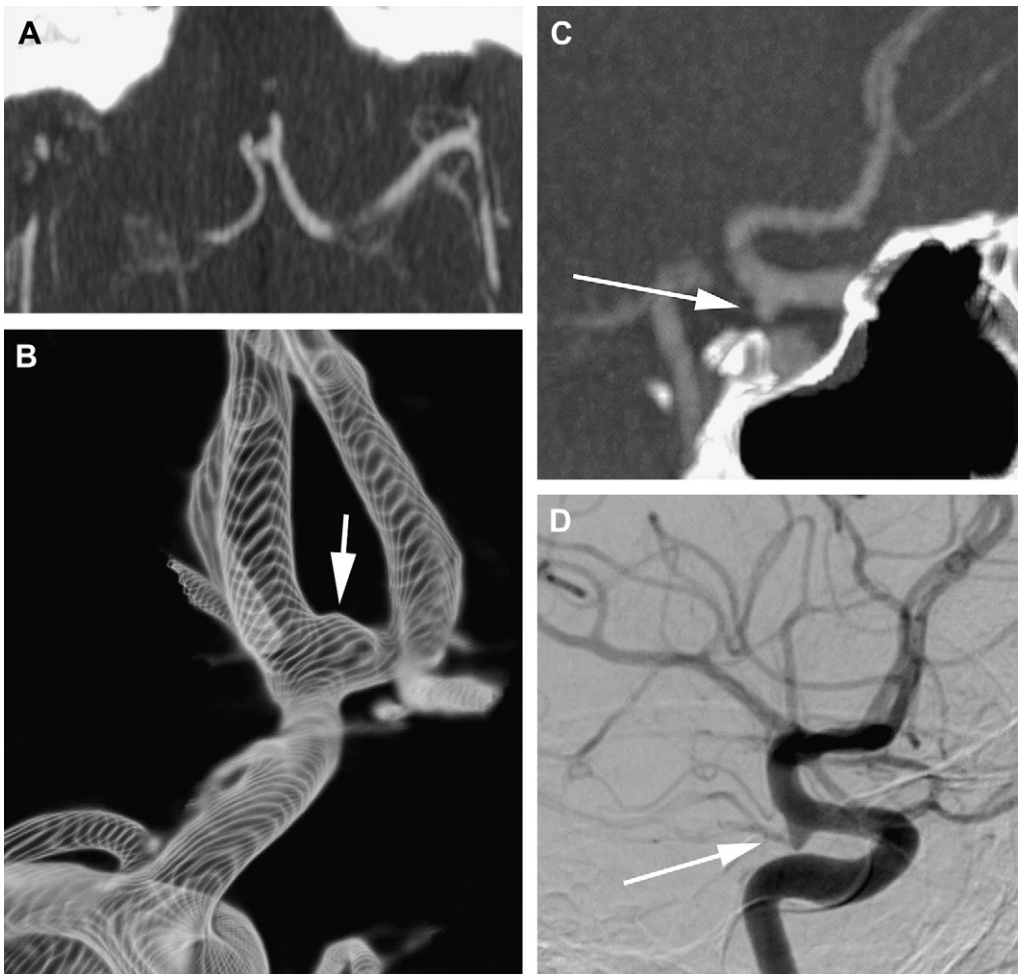

Fig. 7. False positive CTA as seen with this apparent ACOM aneurysm (*A*) that was subsequently found to be a dysplastic vessel segment on rotational DSA (*B*). In a separate patient, suspected PCOM aneurysm on CTA (*C*) was in fact an infundibulum (*D*) with clear visualization of its triangular shape and vessel continuation (*arrow*).

apparent resulting from decreased perfusion to a region of the brain with the development of a transient or permanent neurologic deficit.[53]

The exact cause of VS has not been clearly shown, but it is thought that extra-arterial blood products in contact with the arterial wall triggers a cascade of events at the cellular level that, in effect, culminates in vasoconstriction or overall reduced arterial vascular caliber.[53,56,57] Other factors involved include decreased vascular autoregulation, reversible vasculopathy, and relative hypovolemia.[58,59] A comprehensive review of the current imaging findings and endovascular management of VS is presented elsewhere in this edition of *Neurosurgical Clinics*. In the past, the most likely cause of mortality after SAH was from re-rupture of the aneurysm in the early period after SAH, although because of more aggressive early surgical or endovascular treatment of ruptured aneurysms, this has now been replaced by complications of hydrocephalus and VS as the most common and serious causes of morbidity and mortality after SAH.[60,61]

The incidence of VS after aSAH is estimated at 50% to 70% of patients, with approximately 30% to 50% of those exhibiting symptoms of clinical VS.[62,63] A review of angiography studies of more than 2700 cases of aSAH found the average incidence to be approximately 67%, with the highest incidence occurring between day 10 and day 17 after SAH.[64] In our experience, the peak of VS occurs between day 7 and day 12 after the initial aSAH. The impact on outcome after the emergence of clinical VS (early or delayed) after SAH ranges from 10% to 20% mortality, along with similar increases in morbidity.[64,65] Clearly, VS is

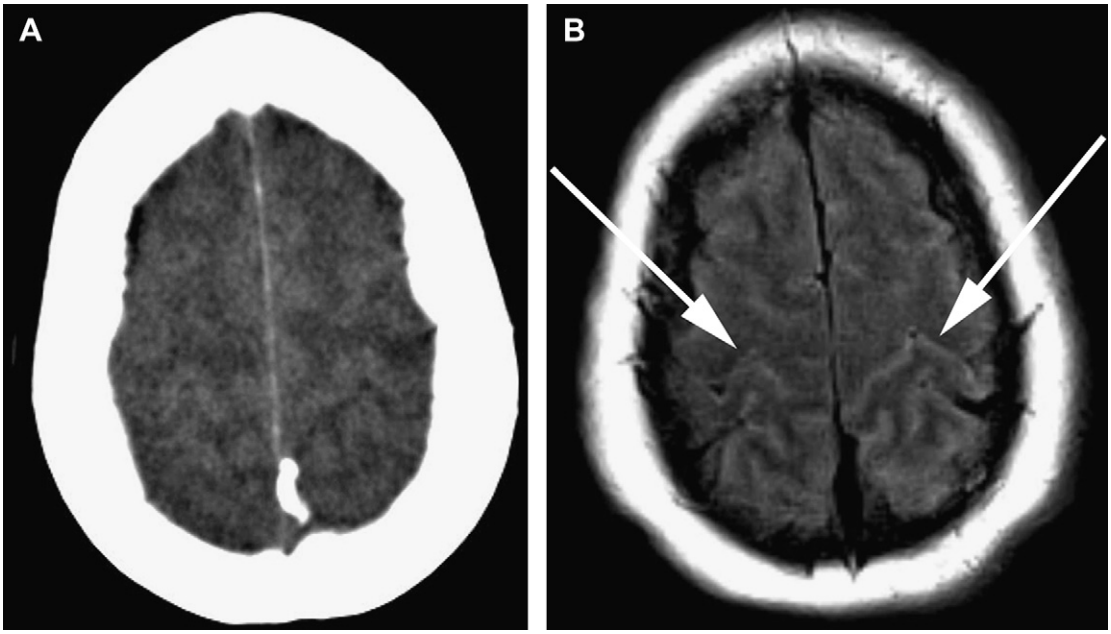

Fig. 8. (*A*) Subtle hyperdensity causing sulcal effacement suggestive of possible acute SAH. This is much better appreciated on FLAIR (*B*) as hyperintensity along the sulci. FLAIR is more sensitive than CT for diagnosing acute subarachnoid bleed.

of diagnostic importance in the management of aSAH, and the early radiographic recognition of VS may allow for institution of therapy and improved outcomes.

The gold standard for the diagnosis of cerebral VS is DSA, although its expense, small potential for neurologic complications, and the need to transfer the patient to the angiography suite make this impractical for use as a screening study for VS.[65] VS is a clinical diagnosis, and radiographic studies and other markers of brain perfusion establish anatomic evidence of diminished vessel caliber. Patients with VS may progress from nonfocal neurologic signs such as confusion, increasing somnolence, and combativeness to focal and localizable neurologic deficits. Radiographic findings often precede such clinical deficits, and thus offer the opportunity to potentially intervene to prevent neurologic injury.

Transcranial Doppler

The initial evidence was provided in 1982 for the use of transcranial Doppler (TCD) in monitoring flow in intracranial arteries and later for the use of this technology in the assessment of arterial VS.[66,67] Much work has been done on the use of TCD in the evaluation of cerebral blood flow, in part because of its relatively inexpensive cost, bedside availability, noninvasive nature, and lack of known adverse side effects from its use as a diagnostic tool.[68,69] Currently, many advocate every other day to twice daily performance of TCD examinations of patients from the first day after presenting with SAH until no longer indicated.[54,70–74] It is also recommended for following the temporal course of angiographic VS during its peak incidence after SAH.[75] The validity of TCD as a monitor for VS has been, however, somewhat controversial.[76] It is an operator-dependent examination, and thin layers of skull that allow insonation by TCD to evaluate blood flow, known as acoustic windows, may be limited in about 8% of patients.[60,76] Limiting factors also include the high false negative rates of VS reported by some as well as the variability among technicians performing the examinations.[77] This may be overcome or lessened with new TCD techniques described in the followingparagraph.[77]

New such technology available for clinical use may make TCD more accurate, and less subject to operator error. This includes Power M-mode (PMD) TCD and transcranial color-coded duplex sonography (TCCS). PMD/TCD facilitates the location of the acoustic temporal window and allows viewing blood flow from multiple vessels at the same time.[56] The display that is used in PMD/TCD allows for color-coded information regarding the directionality of blood flow, and this has allowed for PMD/TCD to be the most commonly used form of TCD performed currently at the bedside.[53] TCCS has expounded on this

improvement, with a 2D representation of the large arteries insonated in addition to color-coded flow directionality information.[53] A study using TCCS has been published recently, where the authors reported comparable accuracy of TCCS and TCD, although improvements in sensitivity of TCCS in detecting MCA VS were noted.[77] An interesting aspect of this study was that comparisons of conventional TCD and TCCS were done on the same patients on the day where DSA was performed. TCCS allowed for the detection of VS at an earlier stage and at lower velocities, which may allow for more timely interventions to potentially intervene and arrest the complications of clinical VS if it were to occur.

The sensitivity of TCD varies depending on the vessel affected by VS, with relatively low sensitivity for supra-clinoid internal carotid and anterior cerebral arteries.[9] In addition, VS of the second- and third-order arteries (small-vessel VS) cannot be studied with transcranial Doppler. TCD has been shown to be specific but not sensitive for VS of the middle cerebral artery when compared with angiography and it is poorly predictive of developing secondary cerebral infarction.[77–79]

Computed Tomography Angiography

CTA has emerged as a potential helpful tool in the evaluation of VS, with relatively good sensitivity and specificity in discovering severe VS of proximal arteries, and with a high negative predictive value in a normal study (**Fig. 9**).[80–82] Early work by Ochi and Takagi showed that CTA was potentially useful in the detection of VS.[82,83] One study interestingly performed CTA followed by DSA in both the patients with VS and without VS seen on CTA, and in this small series, the CTA results were confirmed.[79] Further studies showed that overall correlation between CTA and DSA for a diagnosis of VS was 0.757, but was improved in proximal artery locations and where there was either no spasm or severe spasm (>50% luminal reduction).[84,85] Where CTA performed well, correlation with DSA approached 1.0, and in proximal locations with mild (<30% luminal reduction) or moderate (30%–50% luminal reduction) VS, correlations with DSA were reported as 90% and 95%, respectively. More distal locations with mild or moderate VS were not as evident on CTA, and respective accuracies of 81% and 94% were reported. This has been replicated in other work by Chaudhary.[86]

In a recent article by Yoon and colleagues[84] a series of patients with clinical suspicion for VS underwent both postoperative multidetector-row CTA and DSA. Seventeen patients were studied and a total of 251 arterial segments analyzed. Of the 40 arterial segments with hemodynamically significant stenosis found on DSA, 39 of these lesions were identified with multidetector-row CTA yielding a sensitivity of 97.5%. Unlike prior reports, no difference was found in terms of diagnostic accuracy of distal compared with proximal

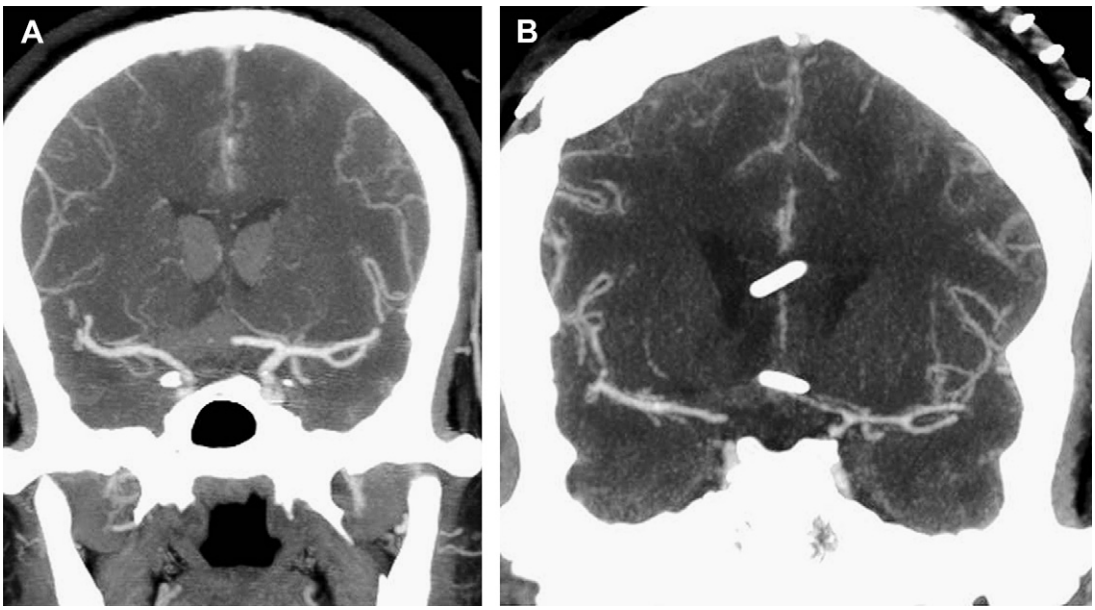

Fig. 9. CTA is good in diagnosing proximal vessel VS as seen in this example. Please note severe narrowing of left distal ICA, left proximal MCA, and left proximal ACA (*A*) compared with the normal caliber of these vessels in baseline CTA (*B*) obtained 4 days earlier.

arterial segments, and this has not been as clearly shown in other subsequent series.[86] There was a trend of overestimation of the degree of spasm by CTA noted; this mostly occurred in the anterior circulation and in the A1 and A2 segment of the ACA, specifically. The authors suggested that CTA would triage resources and allow planning for an interventional procedure such as angioplasty or intra-arterial infusions of vasodilators if findings suggested VS on CTA.[84]

It appears clear that CTA has a role in the diagnosis of VS after aSAH, likely in concert with DSA in select patients, and certainly in cases where CTA findings suggest VS and interventional techniques to arrest cerebral ischemia from VS are used. It seems reasonable, based on current data and with an understanding of the modalities limitations, to use CTA for this purpose as part of a multimodality approach to the diagnosis and treatment of VS after aSAH.

Computed Tomography Perfusion

Coupled with CTA, perfusion studies using CT have created much recent interest. Neither TCD nor DSA provide information about actual brain perfusion during the time period of VS, and this can be directly assessed with CT perfusion (CTP). CTP can provide several quantitative parameters of cerebrovascular hemodynamics. Several perfusion parameters can be obtained from this deconvolution-based technique, including mean transit time (MTT), cerebral blood volume (CBV), and cerebral blood flow (CBF).[87,88] MTT is defined as the average transit time of blood through a given brain region, measured in seconds. The total volume of blood in a given volume of brain, usually measured in milliliters per 100 g of brain tissue, is referred to as CBV. CBF is the volume of blood moving through a given volume of brain per unit time, measured in milliliters per 100 g of brain tissue per minute. MTT and time to peak (TTP) maps have been shown to be the most sensitive in detecting early autoregulation changes in VS and other causes of cerebral ischemia.[88,89] Experimental studies using preclinical models of SAH have shown CTP to reliably predict early mortality and the later development of moderate to severe VS.[90] In this study, MTT was the most reliable predictor of moderate to severe VS and early (within 48 hours) mortality in their model of SAH. Kanazawa and colleagues[91] studied 19 patients with aSAH in which CTP, CTA, and DSA were performed. The authors were able to suggest an MTT threshold that may serve as a criterion for cerebral ischemia and thus require mobilizing angiographic resources for intervention, but this threshold may be institution/equipment specific and requires more study. Binaghi and colleagues[88] published data that confirmed CTP's ability to identify severe VS, which warrants interventional angiographic procedures. All 27 patients in this study had clinical evidence of VS, such as new focal findings, mental status changes, or new aphasia. The DSA showed either mild or moderate VS in 48% and severe VS in 40% of the study subjects. The investigators used CTA as well as CTP, and DSA and CTA correlated with a reported sensitivity and specificity of CTA with DSA of 88% and 99%, respectively. CTP was reported to correctly diagnose the correct vascular territory supplied by the vessel exhibiting VS on DSA. Sensitivity of CTP was found to be 90% in severe VS, with successful detection of severe lesions in all but one patient. Sensitivities were lower for mild or moderate VS. In several of the patients, the decision to treat with interventional techniques was influenced by CTP (**Fig. 10**).

Of these technologies, a combination of CTA and CTP has been suggested as a useful paired diagnostic study.[60] Evidence exists that this combination approach is more effective than TCD in indicating which patients will require endovascular intervention.[92] Additionally, because any change in the examination of a patient with aSAH will prompt noncontrast CT imaging to assess for hydrocephalus, cerebral edema, or new SAH, a CT-based multimodality approach for imaging of VS seems quite practical.

Positron Emission Tomography

The use of positron emission tomography (PET) in the diagnosis of VS and subsequent cerebral ischemia has been investigated in aSAH induced VS.[93–96] PET may play a future role in the multimodal approach to this population and in a subset of these patients but its use is currently limited because of logistics and long acquisition times. Many in this patient population are worsening neurologically during their evaluation for radiographic or other evidence of VS, and are not able to tolerate prolonged diagnostic evaluation such as PET.[92]

Single-Photon Emission Computed Tomography

Single-photon emission computed tomography (SPECT) is able to demonstrate regional cerebral blood flow in patients with neurologic injury by evaluating uptake of radioactive tracer into the brain.[97] Changes in tissue perfusion reflecting functional VS have been seen with SPECT imaging.[98–99] Studies using this technology in the setting of aSAH and VS

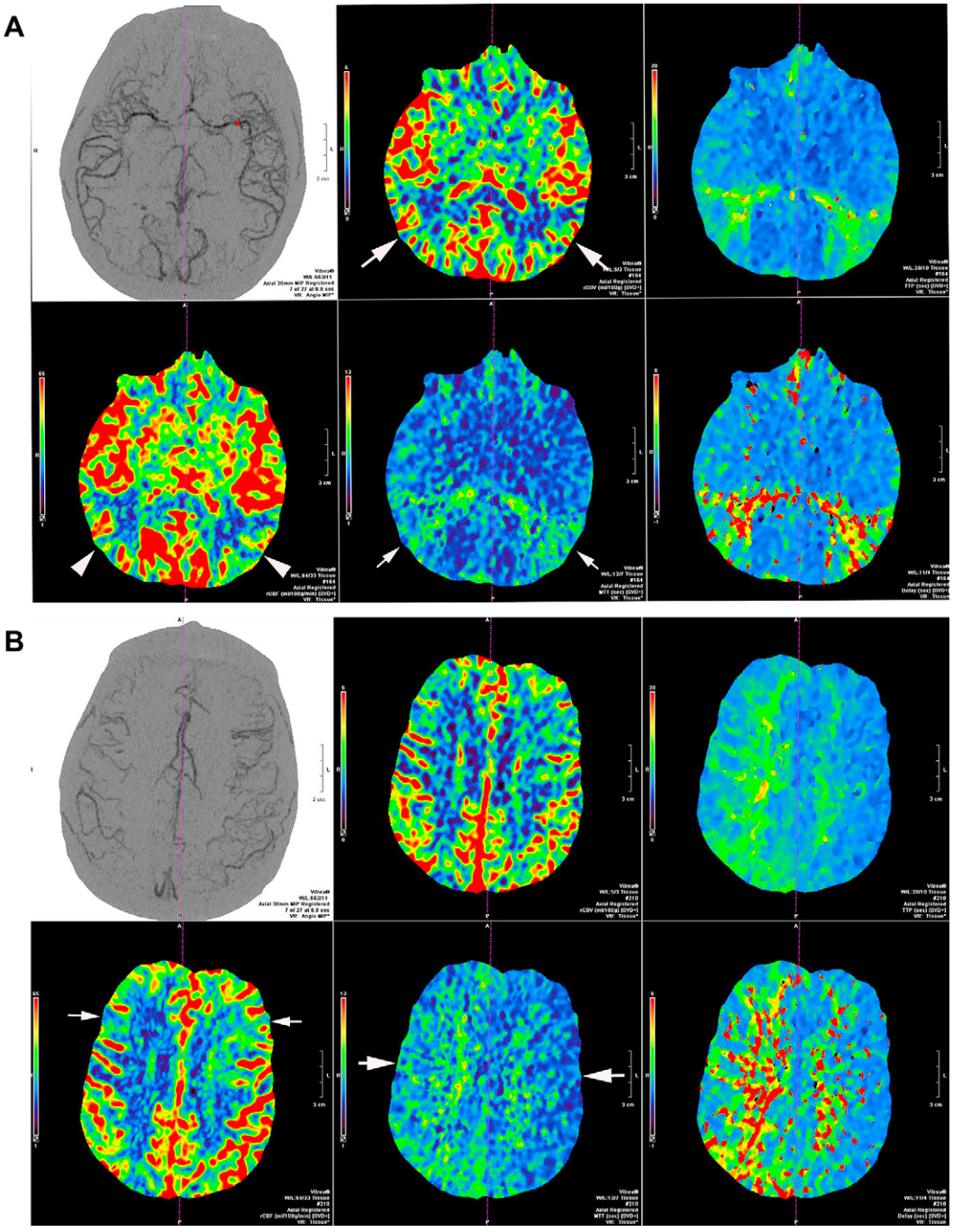

Fig. 10. (*A*) CTP images for suspected VS demonstrate increased MTT in watershed zone between MCA and PCA territory (*arrows* in middle lower image) with corresponding decreased rCBF (*arrowheads* in left lower image) and matched defect on rCBV (*arrows* in middle upper image). (*B*) CTP images from same study at slightly higher level shows increased MTT in large area of right MCA distribution compared with left (middle lower image) suggestive of VS and ischemia. rCBF shows lower values (*arrows* in left lower image) corresponding to already infracted watershed zone between anterior and middle cerebral artery. Subsequent DSA (*C*) demonstrates the expected significant spasm in right distal ICA and proximal MCA and ACA that was treated with intra-arterial nicardipine and balloon angioplasty. Posttreatment DSA (*D*) shows significant improvement in vessel caliber along with clinical improvement. Noncontrast CT image (*E*) obtained a few days later only showed watershed infarcts that were initially noticed during CTP images. Further infarcts were prevented using timely intervention.

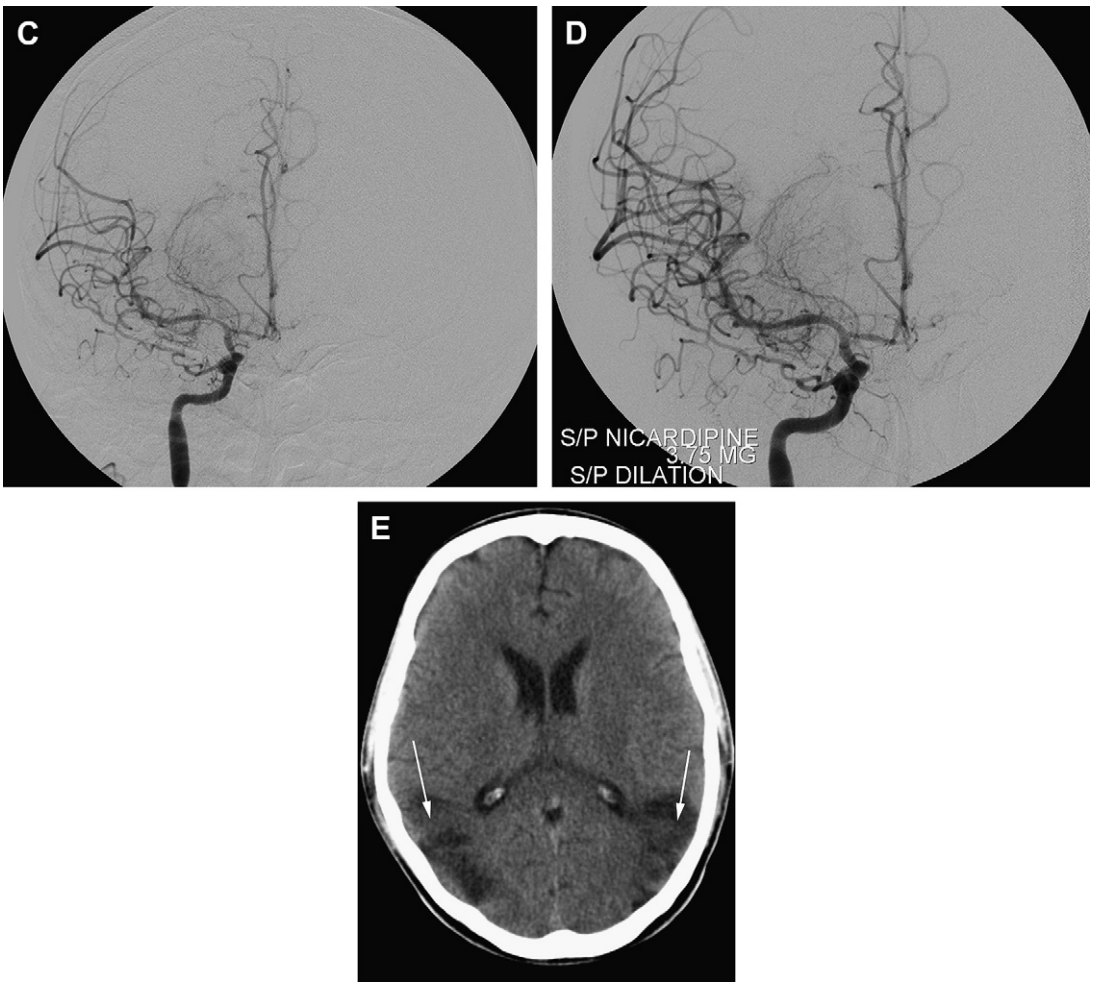

Fig. 10. (*continued*)

have been done, but SPECT has met with controversy over its relative clinical usefulness in this setting.[100–102] At this time, the clinical utility of SPECT in this setting remains unclear.

Magnetic Resonance Angiography

MRA has been used to assess for VS after aSAH, although its limitations include logistics, long time for acquisition, patient characteristics, motion and hardware artifact from surgical clips, or endovascular coils on TOF MRA.[48,49,90] Others have suggested that the most supported role of MRA in SAH is in the case where the SAH is unrelated to aneurysmal rupture, and MRI/MRA may aid in the exclusion of other etiologies.[43] MRA evaluation of cerebral vasoconstriction in other settings such as the reversible cerebral vasoconstriction syndrome unrelated to aSAH, migrainous infarctions, and acute mountain sickness, among others, has been helpful.[103–105] Longer than a decade ago, Tamatani and colleagues[106] reported on the value of MRA to diagnose VS, and compared MRA findings with DSA in a population of 32 patients with aSAH. This study was complicated by poor image quality and inability to evaluate several segments owing to surgical aneurysmal clip or other artifact degrading the images and hampering interpretation. In a study addressing this issue of artifact and titanium-alloy aneurysm clips, data regarding safety and image quality data were provided, and the finding of VS was noted on MRA that was later confirmed on DSA.[107] This technology has not gained widespread acceptance for this purpose to date.

Perfusion-Weighted MRI

Perfusion-weighted MRI (MRP) has gained wide acceptance for use in the setting of stroke, and the use of MRP for detection of cerebral VS has been studied. Although MR technologies

continued to be hampered by logistics, cost, and time constraints, protocols addressing specific issues with MR technology perhaps may lessen some of these issues in the future.[44,50,108,109] In a recent study using diffusion-weighted imaging (DWI), MRP, and DSA, infarct patterns associated with VS were identified. Interestingly, in the setting of moderate VS on DSA, perfusion and diffusion abnormalities were noted remote to areas of VS, implying again that the process of VS involves the cerebral circulation globally.[110] Ohtonari and colleagues[110] presented data recently where DWI, MRP, and SPECT were used to detect VS after aSAH. Seventeen patients were studied, and of the three patients with clinical findings of somnolence, focal neurologic signs, or aphasia, MRP revealed increased MTT with normal CBF and normal to elevated CBV. SPECT failed to show any abnormality during this same period. Medical therapy for VS was instituted, and none of the three patients had permanent infarcts in the area of MRP abnormality. Another paper used MRP and DSA to study 51 patients with aSAH both with and without angiographic evidence of VS. This study was not designed to show or predict ischemic injury as a result of VS, but it did reveal that MRP could clearly indicate impaired cerebral autoregulation via changes in CBV and CBF in the setting of aSAH with or without angiographic VS.[111]

In a recent retrospective review, Hertel and colleagues reported that of 20 patients studied with MRP, 19 showed evidence of perfusion abnormalities in the MTT or TTP maps, and 15 of these had clinical evidence of VS which localized to the region of hypoperfusion on MRP. DWI revealed abnormalities in areas smaller than the MRP abnormalities, indicating a diffusion/perfusion mismatch. The authors concluded that knowledge of this diffusion/perfusion mismatch would allow for interventions to prevent larger areas of ischemia developing in these patients.[109] In the case of this study, intra-arterial vasodilators were used to prevent perfusion abnormalities progressing to infarction in a subset of the population. No adverse events were reported resulting from the MR procedure. This data show promise for the use of MRP in this setting, although concern still exists for the potentially impractical nature of the use of MRP as a screening tool. Further prospective study may also help answer whether knowledge of a perfusion abnormality will result in better outcome by acute introduction of interventional techniques or medical management of VS.

SUMMARY

The management of aSAH and VS presents challenges to the neurosurgeon, neurointensivist, and interventional neuroradiologist. Newer and less invasive modalities for the diagnosis of aSAH and detection of VS are being increasingly used. The current data support use of several of these new techniques in a subset of this population of patients, although DSA still retains its place as the gold standard.

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