American College of Radiology
ACR Appropriateness Criteria®
Cerebrovascular Disease

Variant 1: **Asymptomatic. Structural lesion on physical examination (cervical bruit) and/or risk factors.**

Radiologic Procedure	Rating	Comments	RRL*
US duplex Doppler carotid	8	If positive, consider follow-up with CTA or CE-MRA.	O
MRA neck without IV contrast	8	If positive, consider follow-up with CTA or CE-MRA.	O
MRA neck without and with IV contrast	8	CTA and CE-MRA are comparable noninvasive imaging alternatives each with their own advantages and disadvantages.	O
CTA neck with IV contrast	8	CTA and CE-MRA are comparable noninvasive imaging alternatives each with their own advantages and disadvantages.	☢☢☢
CT head perfusion with IV contrast	5		☢☢☢
MRI head perfusion with IV contrast	5		O
MRI head without IV contrast	5		O
MRI head without and with IV contrast	5		O
CT head without IV contrast	5		☢☢☢
CT head with IV contrast	3		☢☢☢
CT head without and with IV contrast	3		☢☢☢
MRA head without IV contrast	3		O
MRA head without and with IV contrast	3		O
CTA head with IV contrast	3		☢☢☢
Arteriography cervicocerebral	2		☢☢☢

Rating Scale: **1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate** ***Relative Radiation Level**

Variant 2: **Carotid territory or vertebrobasilar TIA, initial screening survey.**

Radiologic Procedure	Rating	Comments	RRL*
MRI head without and with IV contrast	9	Parenchymal brain imaging and CT or MR vascular imaging of the head and neck should be considered.	O
MRI head without IV contrast	8	Parenchymal brain imaging and CT or MR vascular imaging of the head and neck should be considered. Can be useful if there is a contraindication to contrast. MRI is more sensitive than CT for acute infarct.	O
MRA head and neck without IV contrast	8	Can be obtained in conjunction with MRI head. Preferred MR vascular imaging of the head and neck includes noncontrast head MRA and contrast-enhanced neck MRA. Can be useful if there is a contraindication to contrast.	O
MRA head and neck without and with IV contrast	8	Can be obtained in conjunction with MRI head. Preferred MR vascular imaging of the head and neck includes noncontrast head MRA and contrast-enhanced neck MRA.	O
CT head without IV contrast	8	Useful to evaluate for acute intracranial pathology. MRI is more sensitive than CT for acute infarct.	☢☢☢
CTA head and neck with IV contrast	8	CTA can be obtained after NCCT.	☢☢☢
US duplex Doppler carotid	5		O
CT head perfusion with IV contrast	5		☢☢☢
MRI head perfusion with IV contrast	5		O
CT head with IV contrast	3		☢☢☢
CT head without and with IV contrast	3		☢☢☢
Arteriography neck	3		☢☢☢
Arteriography cervicocerebral	3		☢☢☢
Rating Scale: **1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate**			***Relative Radiation Level**

Variant 3: **New focal neurologic defect, fixed or worsening. Less than 6 hours. Suspected stroke.**

Radiologic Procedure	Rating	Comments	RRL*
CT head without IV contrast	9	Parenchymal brain imaging and CT or MR vascular imaging of the head and neck should be considered. Noncontrast head CT is often obtained first to assess for hemorrhage or large infarct. MRI is more sensitive than CT for acute infarct.	☢☢☢
MRI head without IV contrast	8	Parenchymal brain imaging and CT or MR vascular imaging of the head and neck should be considered. Can be useful if there is a contraindication to contrast. Noncontrast head CT is often obtained first to assess for hemorrhage or large infarct. MRI is more sensitive than CT for acute infarct.	O
MRI head without and with IV contrast	8	Noncontrast head CT is often obtained first to assess for hemorrhage or large infarct. MRI head with contrast can be helpful to determine the age of infarct and to evaluate for other causes of symptoms such as tumor or infection.	O
MRA head and neck without IV contrast	8	Can be obtained in conjunction with MRI head. Preferred MR vascular imaging of the head and neck includes noncontrast head MRA and contrast-enhanced neck MRA. Can be useful in patients with renal failure or contrast allergies.	O
MRA head and neck without and with IV contrast	8	Can be obtained in conjunction with MRI head. Preferred MR vascular imaging of the head and neck includes noncontrast head MRA and contrast-enhanced neck MRA.	O
CTA head and neck with IV contrast	8	CTA can be obtained after NCCT.	☢☢☢
CT head perfusion with IV contrast	6		☢☢☢
MRI head perfusion with IV contrast	5		O
Arteriography cervicocerebral	5		☢☢☢
CT head with IV contrast	3		☢☢☢
CT head without and with IV contrast	3		☢☢☢
US duplex Doppler carotid	2		O
Rating Scale: 1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate			*Relative Radiation Level

Variant 4: **New focal neurologic defect, fixed or worsening. Longer than 6 hours. Suspected stroke.**

Radiologic Procedure	Rating	Comments	RRL*
MRI head without IV contrast	8	Parenchymal brain imaging and CT or MR vascular imaging of the head and neck should be considered. Noncontrast head CT is often obtained first to assess for hemorrhage or large infarct. Can be useful if there is a contraindication to contrast. MRI is more sensitive than CT for acute infarct.	O
MRI head without and with IV contrast	8	Parenchymal brain imaging and CT or MR vascular imaging of the head and neck should be considered. Noncontrast head CT is often obtained first to assess for hemorrhage or large infarct. MRI is more sensitive than CT for acute infarct.	O
MRA head and neck without IV contrast	8	Can be obtained in conjunction with MRI head. Preferred MR vascular imaging of the head and neck includes noncontrast head MRA and contrast-enhanced neck MRA. May be useful in patients with renal failure or contrast allergies.	O
MRA head and neck without and with IV contrast	8	Can be obtained in conjunction with MRI head. Preferred MR vascular imaging of the head and neck includes noncontrast head MRA and contrast-enhanced neck MRA.	O
CT head without IV contrast	8	Noncontrast head CT is often obtained first to assess for hemorrhage or large infarct. MRI is more sensitive than CT for acute infarct.	☢☢☢
CTA head and neck with IV contrast	8	CTA can be obtained after NCCT.	☢☢☢
Arteriography cervicocerebral	6		☢☢☢
CT head perfusion with IV contrast	5		☢☢☢
MRI head perfusion with IV contrast	5		O
CT head with IV contrast	3		☢☢☢
CT head without and with IV contrast	3		☢☢☢
US duplex Doppler carotid	2		O
Rating Scale: **1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate**			***Relative Radiation Level**

Variant 5: **Risk of unruptured aneurysm, including patients with polycystic kidney disease, patients who have at least two first-degree relatives with history of subarachnoid hemorrhage (SAH), and those with previously ruptured and treated aneurysms.**

Radiologic Procedure	Rating	Comments	RRL*
CTA head with IV contrast	8	Useful in patients who cannot undergo MRA. Can be useful to confirm findings on MRA.	☢☢☢
MRA head without IV contrast	8	Ideal screening study of choice.	O
MRA head without and with IV contrast	8	Alternative to MRA without contrast.	O
MRI head without IV contrast	6		O
MRI head without and with IV contrast	6		O
CT head without IV contrast	3		☢☢☢
CT head with IV contrast	3		☢☢☢
CT head without and with IV contrast	3		☢☢☢
Rating Scale: 1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate			*Relative Radiation Level

Variant 6: **Clinically suspected acute SAH, not yet confirmed.**

Radiologic Procedure	Rating	Comments	RRL*
CT head without IV contrast	9		☢☢☢
CT head without and with IV contrast	5		☢☢☢
MRI head without IV contrast	5		O
MRI head without and with IV contrast	5		O
CTA head with IV contrast	5		☢☢☢
MRA head without IV contrast	4		O
MRA head without and with IV contrast	4		O
CT head with IV contrast	3		☢☢☢
Arteriography cervicocerebral	2		☢☢☢
MRA neck without IV contrast	2		O
MRA neck without and with IV contrast	2		O
CTA neck with IV contrast	2		☢☢☢
Rating Scale: 1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate			*Relative Radiation Level

Variant 7: **Proven SAH by lumbar puncture or imaging.**

Radiologic Procedure	Rating	Comments	RRL*
Arteriography cervicocerebral	9	Catheter angiography and CTA/MRA are alternative examinations.	☢☢☢
CT head without IV contrast	8	This procedure can be used to follow hemorrhage evolution and to assess for complications related to SAH.	☢☢☢
CTA head with IV contrast	8	Can be performed after NCCT while patient is still on the CT scan table. CTA has similar sensitivity and higher specificity than MRA for aneurysm detection.	☢☢☢
MRA head without IV contrast	8	MRA has similar sensitivity but lower specificity than CTA for aneurysm detection. Useful in patients with renal failure or contrast allergy.	O
MRA head without and with IV contrast	8	MRA has similar sensitivity but lower specificity than CTA for aneurysm detection.	O
MRI head without IV contrast	6		O
MRI head without and with IV contrast	6		O
MRA neck without IV contrast	6		O
MRA neck without and with IV contrast	6		O
CTA neck with IV contrast	6		☢☢☢
US transcranial with Doppler	5		O
CT head without and with IV contrast	5		☢☢☢
CT head with IV contrast	3		☢☢☢
Rating Scale: **1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate**			***Relative Radiation Level**

Variant 8: **Proven SAH, negative angiogram, follow-up.**

Radiologic Procedure	Rating	Comments	RRL*
Arteriography cervicocerebral	8	When both initial catheter angiography and noninvasive studies are negative in patients with nonperimesencephalic SAH, catheter angiography should still be repeated at 1–2 weeks.	☢☢☢
MRA head without IV contrast	8	MRA has similar sensitivity but lower specificity than CTA for aneurysm detection. Useful in patients with renal failure or contrast allergy.	O
MRA head without and with IV contrast	8	MRA has similar sensitivity but lower specificity than CTA for aneurysm detection.	O
CTA head with IV contrast	8	CTA has similar sensitivity and higher specificity for aneurysm detection than MRA. If initial angiography is negative, a noninvasive imaging study should be performed.	☢☢☢
MRI head without IV contrast	7	If performing MRA, consider also obtaining parenchymal brain imaging with MRI to evaluate for nonaneurysmal cause of SAH or other parenchymal brain abnormalities. Can be useful if patient has contraindication to contrast.	O
MRI head without and with IV contrast	7	If performing MRA for vascular imaging, consider also obtaining parenchymal brain imaging with MRI to evaluate for nonaneurysmal cause of SAH or other parenchymal brain abnormalities. Contrast may be helpful to evaluate for enhancing pathology.	O
US transcranial with Doppler	5		O
Arteriography neck	5		☢☢☢
MRA neck without IV contrast	5		O
MRA neck without and with IV contrast	5		O
CT head without IV contrast	5		☢☢☢
CTA neck with IV contrast	5		☢☢☢
CT head with IV contrast	3		☢☢☢
CT head without and with IV contrast	3		☢☢☢
US duplex Doppler carotid	1		O
Rating Scale: 1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate			***Relative Radiation Level**

Variant 9: **Asymptomatic or no new symptoms. Follow-up imaging of previously treated cerebral aneurysms.**

Radiologic Procedure	Rating	Comments	RRL*
Arteriography cervicocerebral	9	Gold standard test.	☢☢☢
MRA head without IV contrast	8	MRA is a noninvasive alternative to DSA. MRA is superior to CTA in evaluation of coiled aneurysms.	O
MRA head without and with IV contrast	8	MRA is a noninvasive alternative to DSA. MRA is superior to CTA in evaluation of coiled aneurysms.	O
CTA head with IV contrast	8	CTA is a noninvasive alternative to DSA. CTA is superior to MRA in evaluation of clipped aneurysms.	☢☢☢
MRI head without IV contrast	5		O
MRI head without and with IV contrast	5		O
CT head without IV contrast	4		☢☢☢
CT head with IV contrast	3		☢☢☢
CT head without and with IV contrast	3		☢☢☢
Rating Scale: **1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate**			***Relative Radiation Level**

Variant 10: **Asymptomatic or no new symptoms. Follow-up imaging of untreated cerebral aneurysms.**

Radiologic Procedure	Rating	Comments	RRL*
Arteriography cervicocerebral	9	Untreated aneurysms are best followed using the same imaging modality on which the aneurysm was initially found. May switch to MRA if stable over time to reduce ionizing radiation dose.	☢☢☢
MRA head without IV contrast	8	Untreated aneurysms are best followed using the same imaging modality on which the aneurysm was initially found.	O
MRA head without and with IV contrast	8	Untreated aneurysms are best followed using the same imaging modality on which the aneurysm was initially found.	O
CTA head with IV contrast	8	Untreated aneurysms are best followed using the same imaging modality on which the aneurysm was initially found. May switch to MRA if stable over time to reduce ionizing radiation dose.	☢☢☢
MRI head without IV contrast	5		O
MRI head without and with IV contrast	5		O
CT head without IV contrast	4		☢☢☢
CT head with IV contrast	3		☢☢☢
CT head without and with IV contrast	3		☢☢☢
Rating Scale: 1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate			***Relative Radiation Level**

Variant 11: **Evaluation for cerebral vasospasm after aneurysmal SAH.**

Radiologic Procedure	Rating	Comments	RRL*
US transcranial with Doppler	8	Ideal screening test.	O
Arteriography cervicocerebral	8	Consider as a next step if noninvasive imaging with TCD US and CTA or MRA are inconclusive.	☢☢☢
CTA head with IV contrast	8	Useful in the setting of indeterminate TCD US.	☢☢☢
MRA head without IV contrast	7	Noninvasive imaging alternative to CTA.	O
MRA head without and with IV contrast	7	Noninvasive imaging alternative to CTA.	O
MRI head without IV contrast	6		O
MRI head perfusion with IV contrast	6		O
MRI head without and with IV contrast	5		O
CT head without IV contrast	5		☢☢☢
CT head perfusion with IV contrast	5		☢☢☢
CT head with IV contrast	3		☢☢☢
CT head without and with IV contrast	3		☢☢☢
Rating Scale: 1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate			***Relative Radiation Level**

Variant 12: **Clinically suspected parenchymal hemorrhage (hematoma), not yet confirmed.**

Radiologic Procedure	Rating	Comments	RRL*
CT head without IV contrast	9	Gold standard test.	☢☢☢
MRI head without IV contrast	8	Alternative to CT. May be as sensitive in detection of hemorrhage, especially with SWI.	O
MRI head without and with IV contrast	7	Alternative to CT. May be as sensitive in detection of hemorrhage, especially with SWI. Contrast is helpful to evaluate for underlying enhancing mass.	O
CT head without and with IV contrast	5		☢☢☢
CT head with IV contrast	4		☢☢☢
MRA head without IV contrast	4		O
MRA head without and with IV contrast	4		O
MR venography head without IV contrast	4		O
MR venography head without and with IV contrast	4		O
CTA head with IV contrast	4		☢☢☢
CT venography head with IV contrast	4		☢☢☢
Rating Scale: 1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate			***Relative Radiation Level**

Variant 13: **Proven parenchymal hemorrhage (hematoma).**

Radiologic Procedure	Rating	Comments	RRL*
MRI head without and with IV contrast	9	Parenchymal imaging and CT or MR vascular brain imaging should be considered. MRI preferred over CT due to greater range of soft-tissue contrast and superior anatomic detail. Contrast is useful to evaluate for underlying enhancing mass or vascular malformation.	O
MRI head without IV contrast	8	Parenchymal imaging and MR or CT vascular brain imaging should be considered. MRI preferred over CT due to greater range of soft-tissue contrast and superior anatomic detail. Can be useful in patients with contraindications to contrast.	O
MRA head without IV contrast	8	Can be obtained in conjunction with MRI head. Useful to evaluate for underlying vascular malformation.	O
MRA head without and with IV contrast	8	Can be obtained in conjunction with MRI head. Useful to evaluate for underlying vascular malformation.	O
CT head without IV contrast	8	Useful to follow-up hemorrhage evolution and evaluate for complications.	☢☢☢
CTA head with IV contrast	8	Can be obtained after NCCT while the patient is still on the CT scan table to evaluate for underlying vascular malformation.	☢☢☢
MR venography head without IV contrast	7	Can be obtained in conjunction with MRI head. Consider MRV if there is concern for venous thrombosis or vascular malformation.	O
MR venography head without and with IV contrast	7	Can be obtained in conjunction with MRI head. Consider MRV if there is concern for venous thrombosis or vascular malformation.	O
CT venography head with IV contrast	7	Consider CTV if there is concern for venous thrombosis or vascular malformation. CTV can be obtained following NCCT.	☢☢☢
MRA head and neck without and with IV contrast	6		O
Arteriography cervicocerebral	6		☢☢☢
CT head without and with IV contrast	6		☢☢☢
CT venography head and neck with IV contrast	5		☢☢☢
MRA head and neck without IV contrast	5		O
CTA head and neck with IV contrast	5		☢☢☢
CT head with IV contrast	4		☢☢☢
Rating Scale: 1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate			***Relative Radiation Level1**

Variant 14: **Evaluation of high-flow vascular malformations.**

Radiologic Procedure	Rating	Comments	RRL*
Arteriography cervicocerebral	9	Gold standard test. Usually performed after initial noninvasive imaging with MR or CT.	☢☢☢
MRI head without and with IV contrast	8	Parenchymal imaging and CT or MR vascular brain imaging should be considered. MRI is superior to CT for parenchymal evaluation due to greater range of soft-tissue contrast and improved anatomic detail. It is helpful in determining the location of the vascular malformation in relation to eloquent brain areas.	O
MRA head without IV contrast	8	Can be obtained in conjunction with MRI.	O
MRA head without and with IV contrast	8	Can be obtained in conjunction with MRI.	O
CTA head with IV contrast	8	Can be performed following NCCT head. Can be useful in patients with contraindications to MRI.	☢☢☢
MR venography head without IV contrast	7	Can be obtained in conjunction with MRI head. Can be useful in patients with contraindications to contrast.	O
MR venography head without and with IV contrast	7	Can be obtained in conjunction with MRI.	O
CT venography head with IV contrast	7	Can be performed following NCCT head. Can be useful in patients with contraindications to MRI.	☢☢☢
MRA neck without and with IV contrast	7	Can be obtained in conjunction with MRI head. May be useful to evaluate the anatomy, patency, and involvement of the neck vasculature. Head only vascular imaging may often be adequate for follow-up imaging.	O
CTA neck with IV contrast	7	Can be performed following NCCT head. May be useful to evaluate the anatomy, patency, and involvement of the neck vasculature in the initial imaging workup. Head only vascular imaging may often be adequate for follow-up.	☢☢☢
CT venography head and neck with IV contrast	6		☢☢☢
MRI head without IV contrast	6		O
MRA head and neck without IV contrast	6		O
CT head without and with IV contrast	5		☢☢☢
CT head without IV contrast	5		☢☢☢
CT head with IV contrast	4		☢☢☢
Rating Scale: **1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate**			***Relative Radiation Level**

Variant 15: **Suspected dural venous sinus thrombosis.**

Radiologic Procedure	Rating	Comments	RRL*
MR venography head without and with IV contrast	9	Parenchymal imaging and vascular brain imaging with CT or MR should be considered. With contrast is preferred over MRV without contrast.	O
MR venography head without IV contrast	8	Parenchymal imaging and vascular brain imaging with CT or MR should be considered. Can be useful in the patient with a contraindication to contrast.	O
CT venography head with IV contrast	8	CTV can be obtained while the patient is still on the CT scan table after NCCT and can be obtained rapidly in the emergent setting. Postcontrast image timing can be optimized for evaluation of the intracranial venous structures.	☢☢☢
MR venography head and neck without and with IV contrast	8	Can be obtained in conjunction with MRI head. MRV without and with contrast is superior to MRV without contrast due to problems noncontrast MRV has with slow and turbulent flow. Neck MRV can be useful to evaluate involvement of the neck vessels.	O
CT head without and with IV contrast	7	Can be useful if there is contraindication to MRI. Head CTV with contrast provides superior evaluation of the intracranial venous structures.	☢☢☢
CT head without IV contrast	7	Useful in initial evaluation of symptoms and in follow-up.	☢☢☢
MRI head without and with IV contrast	7	Useful to evaluate for complications of CVT including infarct and hemorrhage; to visualize thrombus; to determine the age of infarct; and to evaluate for other pathologies.	O
MRI head without IV contrast	7	Can be useful if there is a contraindication to contrast. Can evaluate for CVT complications including infarct and hemorrhage and to visualize thrombus.	O
CT venography head and neck with IV contrast	7	CTV can be obtained while the patient is still on the CT scan table after NCCT. Postcontrast image timing can be optimized for evaluation of the venous structures. Can be useful to evaluate involvement of the neck vessels.	☢☢☢
CT head with IV contrast	6		☢☢☢
MR venography head and neck without IV contrast	6		O
Catheter venography cervicocerebral	5		☢☢☢
Rating Scale: 1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate			***Relative Radiation Level**

Variant 16: **Central nervous system vasculitis.**

Radiologic Procedure	Rating	Comments	RRL*
MRI head without and with IV contrast	8	Parenchymal brain imaging and CT or MR vascular imaging of the head and neck should be considered. MRI has a greater range of soft-tissue contrast and superior anatomic detail compared to CT and is more sensitive at detecting acute infarcts and scattered white-matter lesions. Postcontrast imaging can be useful to determine the age of infarcts.	O
MRA head without and with IV contrast	8	Can be obtained in conjunction with MRI head.	O
MRA head without IV contrast	8	Can be obtained in conjunction with MRI head. Can have difficulty with slow or turbulent flow.	O
Arteriography cervicocerebral	8	Noninvasive imaging should be performed first.	☢☢☢
CTA head with IV contrast	8	Can be performed in conjunction with NCCT head. CTA has higher spatial resolution than MRA.	☢☢☢
MRA head and neck without and with IV contrast	7	Can be obtained in conjunction with MRI head. Neck imaging may be useful to evaluate involvement of the neck vessels.	O
MRA head and neck without IV contrast	7	Can be obtained in conjunction with MRI head. Useful in patients with renal failure or contrast allergies. Neck imaging may be useful to evaluate involvement of the neck vessels.	O
CTA head and neck with IV contrast	7	CTA can be obtained in conjunction with NCCT head and has higher spatial resolution than MRA. Neck imaging may be useful to evaluate involvement of the neck vessels.	☢☢☢
MRI head without IV contrast	7	MRI has a greater range of soft-tissue contrast and superior anatomic detail compared to CT and is more sensitive at detecting acute infarcts and scattered white-matter lesions. Can be useful if patient has contraindication to contrast.	O
CT head without IV contrast	5		☢☢☢
CT head without and with IV contrast	4		☢☢☢
US duplex Doppler carotid	4		O
CT head with IV contrast	3		☢☢☢
Rating Scale: **1,2,3 Usually not appropriate; 4,5,6 May be appropriate; 7,8,9 Usually appropriate**			***Relative Radiation Level**

CEREBROVASCULAR DISEASE

Expert Panel on Neurologic Imaging: Michael B. Salmela, MD[1]; Shabnam Mortazavi, MD[2]; Bharathi D. Jagadeesan, MD[3]; Daniel F. Broderick, MD[4]; Judah Burns, MD[5]; Tejaswini K. Deshmukh, MB, MS[6]; H. Benjamin Harvey, MD, JD[7]; Jenny Hoang, MBBS[8]; Christopher H. Hunt, MD[9]; Tabassum A. Kennedy, MD[10]; Alexander A. Khalessi, MD, MS[11]; William Mack, MD[12]; Nandini D. Patel, MD[13]; Joel S. Perlmutter, MD[14]; Bruno Policeni, MD[15]; Jason W. Schroeder, MD[16*]; Gavin Setzen, MD[17]; Matthew T. Whitehead, MD[18]; Rebecca S. Cornelius, MD[19]; Amanda S. Corey, MD.[20]

Summary of Literature Review

Introduction/Background

Diseases of the cerebral vasculature represent a heterogeneous group of ischemic and hemorrhagic etiologies, which often manifest clinically as an acute neurologic deficit also known as stroke or less commonly with symptoms such as headache or seizures. Stroke is the fourth leading cause of death behind heart disease, cancer, and chronic lower respiratory disease and is a leading cause of serious long-term disability in the United States. Approximately 795,000 people in the United States experience a new or recurrent stroke each year, with 610,000 being their first stroke and 185,000 being recurrent strokes. Eighty-seven percent of strokes are ischemic, 10% are due to intracerebral hemorrhage (ICH), and 3% are secondary to subarachnoid hemorrhage (SAH) [1].

The last 2 decades have seen significant developments in the screening, diagnosis, and treatment of ischemic and hemorrhagic causes of stroke with advancements in computed tomography (CT) and magnetic resonance imaging (MRI) technology, changes in stroke imaging algorithms, and novel treatment devices and techniques such as intravenous tissue plasminogen activator (IV-tPA), carotid artery stenting, intra-arterial therapy (IAT) of ischemic stroke, and endovascular embolization of vascular malformations. These advancements have helped achieve decreases in the annual stroke death rate and number of stroke deaths by 35.8% and 22.8%, respectively, from 2000–2010 [1]. Over the past 2 years multiple randomized controlled trials have conclusively demonstrated the superiority of mechanical thrombectomy when compared to IV-tPA in the treatment of acute ischemic stroke from large vessel occlusive disease [2-5].

Overview of Imaging Modalities

Multiple different imaging modalities can be utilized in the evaluation of cerebrovascular disease, including ultrasound (US), CT, CT angiography (CTA), CT venography (CTV), CT perfusion (CTP), MRI, MR angiography (MRA), MR venography (MRV), MR perfusion, and digital subtraction angiography (DSA). The different imaging modalities all have their own niches in the evaluation of cerebrovascular disease and their own advantages and disadvantages.

Ultrasound

US is commonly used in screening for carotid artery stenosis and to evaluate for cerebral artery vasospasm after SAH. Advantages of US include its lack of ionizing radiation, low cost, and ability to be performed at the patient's bedside. Disadvantages of US include heavy operator dependence and occasional difficulty in obtaining an adequate acoustic window to visualize the area of interest. Additionally, vascular US is limited in the

[1]Research Author, University of Minnesota, Minneapolis, Minnesota. [2]Research Author, University of Minnesota, Minneapolis, Minnesota. [3]Principal Author ,University of Minnesota, Minneapolis, Minnesota. [4]Mayo Clinic Florida, Jacksonville, Jacksonville, Florida. [5]Montefiore Medical Center, Bronx, New York. [6]Children's Hospital of Wisconsin, Milwaukee, Wisconsin. [7]Massachusetts General Hospital, Boston, Massachusetts. [8]Duke University Medical Center, Durham, North Carolina. [9]Mayo Clinic, Rochester, Minnesota. [10]University of Wisconsin Hospital and Clinic, Madison, Wisconsin. [11]University of California San Diego Medical Center, San Diego, California, neurosurgical consultant. [12]University of Southern California, Los Angeles, California, neurosurgical consultant. [13]Fairfax Radiology Consultants PC, Fairfax, Virginia. [14]Washington University School of Medicine, Saint Louis, Missouri, American Academy of Neurology. [15]University of Iowa Hospitals and Clinics, Iowa City, Iowa. [16]Walter Reed National Military Medical Center, Bethesda, Maryland. [17]Albany ENT & Allergy Services PC, Albany, New York, American Academy of Otolaryngology-Head and Neck Surgery. [18]Children's National Medical Center, Washington, District of Columbia. [19]Specialty Chair, University of Cincinnati Medical Center, Cincinnati, Ohio. [20]Panel Chair, Emory Universtiy, Atlanta, Georgia.

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evaluation of the proximal common carotid and distal internal carotid arteries (ICAs), tandem vascular lesions, near occlusion, and heavily calcified vessels.

Computed Tomography

CT technology continues to improve since its introduction in the early 1970s with improved radiation dose reduction techniques such as iterative reconstruction and tube current modulation as well as reduced scan times secondary to multislice CT technology. CT is used across the spectrum of cerebrovascular diseases. Noncontrast CT (NCCT) of the head is the first-line imaging test to evaluate for intracranial hemorrhage in patients presenting with acute stroke, whether acute ischemic stroke (AIS) or hemorrhagic stroke. CT is also very sensitive in detecting calcification, which can be important in lesion characterization. Contrast-enhanced CT of the head is not commonly used but may be utilized when contrast-enhanced brain MRI cannot be performed. MRI is preferred for evaluation of the brain parenchyma because of the superior soft-tissue contrast resolution of MRI compared to CT.

CTA is versatile and can be used to evaluate for stenosis, occlusion, dissection, vasculitis, aneurysm, or nonaneurysmal vascular malformation in the vessels of the head and neck. CTV can be used in the evaluation of venous sinus thrombosis and vascular malformations. CTP can be used to evaluate cerebrovascular reserve; however, its role in the evaluation of acute stroke remains unproven because of sensitivity to motion, low signal-to-noise ratio, and variation among software packages. CTA, CTV, and CTP all require the use of intravenous (IV) iodinated contrast, which may not be feasible in patients with renal dysfunction or contrast allergy.

Advantages of CT include rapid image acquisition with low susceptibility to motion, ready availability, and relatively high spatial resolution. However, disadvantages of CT include exposing the patient to ionizing radiation and, with the use of IV iodinated contrast material, the risk of contrast allergy and contrast-induced nephropathy.

Magnetic Resonance Imaging

MRI offers superb, unmatched soft-tissue contrast resolution, and it is widely used in the evaluation of cerebrovascular disease. MRI of the brain is usually performed without and with gadolinium-based IV contrast in the evaluation of acute stroke and transient ischemic attack (TIA), and in further evaluation of hemorrhagic brain lesions. A limited noncontrast brain MRI can be performed in the acute stroke patient with diffusion-weighted imaging (DWI), apparent diffusion coefficient (ADC) map, and fluid-attenuated inversion recovery (FLAIR) to evaluate for infarct. Currently, the most common clinical MRI scanners have field strengths of 1.5T and 3T. Increasing field strength leads to increased signal-to-noise ratio, increased susceptibility effects, and increased chemical shift artifact. MRI may be unable to be performed in patients with claustrophobia, morbid obesity, or presence of cardiac device or metal within the patient. Caution should be used when administering IV gadolinium contrast in patients with renal dysfunction or contrast allergy. The American College of Radiology (ACR) documents on MRI safety and contrast media provide more detailed safety information [6,7].

MRA of the brain or cervical arteries can be performed without or with contrast, depending on the clinical scenario. Noncontrast MRA techniques include time-of-flight MRA (TOF-MRA), phase-contrast MRA (PC-MRA), and blood oxygenation level-dependent (BOLD) MRV or susceptibility-weighted imaging (SWI). TOF-MRA relies on flow-related enhancement and 3-D TOF-MRA offers excellent spatial resolution. It is commonly used in imaging the circle of Willis in acute stroke. However, TOF-MRA has difficulty evaluating slow and turbulent flow and has poor suppression of background short T1 signal from thrombus. PC-MRA utilizes the difference in phase between moving and stationary blood and offers information on the direction and velocity of moving blood. Additionally, PC-MRA has advantages over TOF-MRA in that PC-MRA is able to evaluate slow flow well and is able to differentiate thrombus with short T1 signal from moving blood. This makes PC-MRA a good candidate for evaluating dural venous sinus thrombosis. However, a drawback of PC-MRA is its long imaging acquisition time. Contrast-enhanced MRA (CE-MRA) utilizes the T1-shortening effects of gadolinium-based IV contrast agents and is less susceptible to image degradation due to slow and turbulent flow. CE-MRA is commonly used in the evaluation of the cervical vessels in the workup of acute stroke and TIA. CE-MRA is also useful in the evaluation of cerebral vascular malformations such as arteriovenous malformations (AVMs) and dural arteriovenous fistulae (AVFs). Recent advances in 4-D MRA with time-of-arrival maps as well as the utilization of arterial spin labeling techniques shows promise in noninvasive characterization of AVMs and dural AVFs [8-12]. Arterial spin labeling with selective arterial excitation shows great promise, but is not yet mainstream when it comes to the detection and characterization of AVMs [13]. MRV can be used in the evaluation of cerebral venous thrombosis (CVT) and vascular malformations and can be performed without or

with IV contrast, similar to MRA, with techniques including TOF, PC, BOLD or SWI, and contrast-enhanced MRV. MR perfusion imaging is similar to CTP and its utility also remains questionable in the evaluation of acute stroke due to sensitivity in patient motion as well as low signal-to-noise ratio.

Digital Subtraction Angiography
DSA remains the gold standard imaging test to evaluate for carotid artery stenosis, cerebral artery aneurysms, vasculitis, and high-flow cerebral vascular malformations. However, DSA is an invasive imaging test with potential complications and is therefore usually not a first-line imaging test except perhaps in patients with acute SAH. However, it remains an integral part in the evaluation and management of patients with cerebrovascular malformations and aneurysms.

Stroke Overview

Transient Ischemic Attack
TIA has traditionally been described as a focal neurologic deficit that resolves within 24 hours. However, up to 50% of patients with the traditional definition of TIA based on the duration of symptoms were found to have infarcts on DWI [14-16]. Subsequently, in 2009 the American Stroke Association proposed a tissue-based definition of TIA as "a transient episode of neurological dysfunction caused by focal brain, spinal cord, or retinal ischemia, without acute infarction" [14]. TIA patients are at high risk for future stroke. TIA patients have a 5.3% chance of stroke within 48 hours, 21% of which are fatal [17]. Up to 20% of TIA patients suffer a stroke within 3 months [18-20]. Additionally, the 10-year risk for suffering a stroke, myocardial infarction, or death in a TIA patient is as high as 43% [21,22]. Because of the imminent high risk of future stroke associated with TIA, imaging workup of TIA should be performed as soon as possible.

Stroke
Stroke is a lay term used to describe a sudden-onset neurologic deficit and can be categorized into ischemic and hemorrhagic etiologies.

Ischemic Stroke
Ischemic stroke is responsible for 87% of all strokes and imaging plays a key role in its management [1]. Causes of ischemic stroke include thrombi, emboli, and hypoperfusion (watershed infarcts). The main imaging modalities used in the evaluation of ischemic stroke include head NCCT, CTA of the head and neck, brain MRI, and MRA of the head and neck. The clinical scenario and time since symptom onset determines which imaging modalities are to be used in the workup of ischemic stroke and its underlying causes. Screening for carotid artery stenosis can be performed with duplex US, MRA, or CTA depending on the scenario. Treatment of ischemic stroke has dramatically changed over the last 20 years. In 1996 the U.S. Food and Drug Administration (FDA) approved the use of IV-tPA for thrombolytic therapy of AIS. Subsequently, mechanical thrombectomy/thromboaspiration has also developed.

Treatment of Ischemic Stroke
The goal of ischemic stroke treatment is the salvage of ischemic but yet-to-be-infarcted penumbral brain tissue that surrounds an infarct core. The current FDA-approved treatment for AIS symptoms is IV-tPA within 3 hours of symptom onset, and the recommended initial imaging study is an NCCT to exclude intracranial hemorrhage. However, in 2009 the American Heart Association approved the use of IV-tPA up to 4.5 hours from symptom onset [23]. Interestingly, studies have found that many ischemic stroke patients have large ischemic penumbras up to 24 hours after symptom onset, suggesting the possibility of salvageable tissue at up to 24 hours and the potential for extension of the treatment window beyond 4.5 hours [24,25].

Significant improvements in IAT for AIS have occurred since 1999, with improved revascularization rates now up to 90% or more with current techniques, as opposed to 50% a decade earlier [26-29]. Despite these remarkable developments in IAT, the evidence from 3 large trials, namely, IMS III, SYNTHESIS Expansion, and MR RESCUE [30-32], had led to renewed concerns regarding the additive benefits of IAT over IV-tPA in acute stroke patients. Most recently, however, the data from 4 studies, including MR CLEAN, EXTEND-IA, ESCAPE, and SWIFT PRIME, have shown that patients who undergo endovascular treatment within 6 hours from symptom onset for anterior circulation, proximal large-vessel occlusion AIS do indeed have significantly better outcomes when compared to patients who are treated with IV-tPA alone, and this is now the standard of care in this situation [2-5].

Hemorrhagic Stroke

Hemorrhagic stroke represents 13% of all strokes, with ICH causing 10% and SAH causing 3% of all strokes [1]. Subdural and epidural hemorrhages are not included in these statistics and are more commonly associated with trauma. Although hemorrhagic strokes are significantly less common than ischemic strokes, hemorrhagic strokes are more severe, with a higher risk of death than ischemic stroke [33]. This increased relative risk declines with time and becomes equal to that of ischemic stroke at 3 months [33]. Numerous underlying etiologies are responsible for these intracerebral and SAHs, including hypertension, amyloid angiopathy, AVMs, cavernous malformations, hemorrhagic neoplasms, cerebral aneurysms, venous sinus thrombosis, dural AVFs, and nonaneurysmal SAH.

Noncontrast head CT remains the initial imaging test of choice in patients presenting with stroke symptoms because of its speed of image acquisition, high sensitivity for acute hemorrhage, wide availability on a 24-hour basis, lack of absolute contraindications, and ease of patient monitoring. Catheter arteriography remains the gold standard imaging test to evaluate for cerebral aneurysm, AVM, and dural arteriovenous fistula. CTA, MRA, and contrast-enhanced brain MRI can provide valuable additional information in the workup of ICH and SAH.

Variant 1: Asymptomatic. Structural lesion on physical examination (cervical bruit) and/or risk factors.

Screening for carotid artery stenosis is an important tool in the prevention of ischemic stroke since carotid artery disease is responsible for 10%–20% of strokes. Studies have shown that treatment of carotid artery stenosis with endarterectomy or carotid artery stenting is effective in reducing the risk of stroke in populations of symptomatic and asymptomatic patients who are selected based on the severity of luminal diameter narrowing in the proximal ICAs and who have access to procedures with reasonable risk profiles [34-39]. Multiple noninvasive imaging techniques have been developed to evaluate for carotid artery stenosis, including duplex US, CTA, and MRA. These noninvasive imaging techniques all have advantages and limitations. They all have high sensitivities and specificities for detecting high-grade treatable carotid artery stenosis [40]. Choosing an imaging modality to evaluate for carotid artery stenosis depends on the clinical scenario as well as patient factors such as age, kidney function, contrast allergies, claustrophobia, presence of morbid obesity, and presence of cardiac devices or metal within the patient.

Duplex US is an effective low-cost method of initial screening for carotid stenosis. However, it is operator dependent and can have difficulty with artifact due to calcified plaque and is limited in the evaluation of near occlusion, tandem lesions, and lesions at the distal carotid and carotid origin [41].

CTA and MRA are often used for further evaluation of patients with positive duplex US findings. MRA is an excellent screening test since it is noninvasive and does not utilize ionizing radiation. CE-MRA is superior to noncontrast TOF-MRA because it is less affected by slow and turbulent flow, particularly at the carotid bifurcation. The combination of duplex US and CE-MRA is a common choice for carotid artery evaluation [42-44]. Limitations of MRA include difficulty in patients with claustrophobia and the risk of nephrogenic systemic sclerosis with gadolinium contrast agents in specific patients. Also, certain medical devices are not MR safe or require additional evaluation and patient preparation and monitoring during scanning. Retained metal fragments in the patient might also not be considered safe in the MRI scanner. The ACR documents on MRI safety and contrast media provide more detailed safety information [6,7]. CTA has advantages over MRA including its superior spatial resolution, rapid image acquisition, and significantly decreased susceptibility to motion artifacts. CTA is also less prone than MRA to artifacts from calcification and is better able to evaluate slow flow and tandem lesions. In fact, dual-energy CTA has been shown to be helpful in evaluating carotid stenosis in the presence of calcified plaques; however, with this technique, there could be overestimation of high-grade stenosis [45,46]. However, limitations of CTA include radiation exposure to the patient, necessity of IV contrast, and risk of contrast allergy and contrast nephropathy. All of these factors need to be taken into account when deciding which noninvasive imaging modality to use for carotid artery evaluation. If CTA or MRA are inconclusive or if they contradict findings from duplex US, DSA should be performed.

Most of the emphasis of carotid artery imaging has focused on luminal narrowing given its importance shown by trials such as NASCET. However, further characterization of carotid atherosclerotic plaque features such as surface ulceration, plaque rupture, thin fibrous capsule, lipid-rich necrotic core, and presence of inflammation with the help of high-resolution CTA and MRA may provide additional prognostic information [47-49]. These techniques could also possibly be used to follow effectiveness of medical therapy over time [47].

Investigations of cerebrovascular reserve by using CT and MR perfusion with acetazolamide challenge have shown some promising results [50,51]. These methods may identify patients with carotid artery stenosis who are at higher risk for stroke from decreased cerebrovascular reserve and poor collateral circulation.

Variant 2: Carotid territory or vertebrobasilar TIA, initial screening survey.

Imaging evaluation of TIA should be performed as soon as possible because of the associated high risk of future stroke and is ideally performed with imaging of the brain parenchyma including a contrast-enhanced brain MRI along with vascular imaging of the head and neck including TOF-MRA of the circle of Willis and CE-MRA of the cervical vessels [14]. An example of a TIA-protocol MRI includes a contrast-enhanced brain MRI with sequences including DWI, ADC, T1-weighted imaging, T2-weighted imaging, FLAIR, T2*-weighted imaging, or SWI, and postcontrast T1-weighted imaging, as well as TOF-MRA of the circle of Willis and CE-MRA of the cervical vessels. If there is concern for carotid artery dissection, axial fat-suppressed T1-weighted images through the neck should be obtained. This combination of sequences allows for identification of other causes for the patient's symptoms and allows the identification of the presence of infarct and its age [15]. CT and CTA can alternatively be performed if there is contraindication to MRI. However, CT is significantly less sensitive for infarct and parenchymal lesions and CTA requires the use of IV iodinated contrast and exposes the patient to ionizing radiation [16]. If neck CTA or MRA cannot be performed to evaluate the vasculature of the neck, carotid duplex US may be useful. CTP may be used to evaluate for ischemia when MRI is contraindicated or not available [17].

Variant 3: New focal neurologic defect, fixed or worsening. Less than 6 hours. Suspected stroke.

The time period since symptom onset in this variant has changed since the last version of the ACR Appropriateness Criteria on cerebrovascular disease. In the previous version the variants of new focal neurologic deficit included time windows of <3 hours, 3–24 hours, and >24 hours since symptom onset. A major factor in determining the previous time windows was the FDA-approved time window of <3 hours since symptom onset for treatment of acute stroke with IV-tPA. However, recently the data from multiple randomized endovascular studies have shown that patients with large-vessel occlusion (ICA terminus or middle cerebral artery [MCA], M1 segment) who undergo endovascular treatment within 6 hours from symptom onset for anterior circulation AIS do indeed have significantly better outcomes when compared to patients who are treated with IV-tPA alone [2-5]. Therefore, the new variants include time windows of <6 hours and >6 hours.

The goal of imaging in this scenario is to identify hemorrhage and in the absence of hemorrhage to differentiate the extent of permanently damaged infarcted brain tissue (infarct core) from the extent of salvageable but ischemic surrounding brain tissue (ischemic penumbra). NCCT is the first-line imaging study in the workup of acute stroke to rule out intracranial hemorrhage because of its speed, high sensitivity for hemorrhage, and ready availability. The Alberta Stroke Program Early CT (ASPECT) score obtained from a noncontrast head CT can be used to determine the extent of already established ischemic cerebral infarction and the risk of parenchymal hemorrhage following IV-tPA [52,53]. The ASPECT score has been widely used in clinical trials, and it has been repeatedly validated.

After ruling out intracranial hemorrhage and large infarct with NCCT, IV-tPA is used as the first-line treatment for ischemic stroke (in the absence of any of the well-established contraindications for tPA administration). When possible, the next step in the imaging algorithm should be CTA of the head and neck to evaluate for large-vessel occlusion such as the distal ICA or the proximal MCA. The vessels of the neck need to be included to identify atherosclerotic carotid artery disease or dissection with or without tandem occlusion of intracranial arteries. This can be performed immediately after the NCCT without delaying IV-tPA treatment. The importance of identifying large vessel occlusion lies in the fact that IV-tPA has low likelihood of recanalizing these large-vessel occlusions, with only 6% success in recanalizing the distal ICA and 30% success in recanalizing the proximal MCA [54]. This large-vessel occlusion is a possible target for pharmaco-mechanical IAT. At this stage, patients with a distal ICA or proximal MCA clot, National Institutes of Health Stroke Scale (NIHSS) of >8, and an ASPECT score of >7 are often taken to the angiography suite for further intervention. The role of CTP in this scenario is presently unclear and not well substantiated, leading to a gradual decline in its usage in the setting of AIS [55-61]. CTP images suffer from high noise and low signal-to-noise and contrast-to-noise ratios, as well as exquisite sensitivity to patient movement [58]. Additionally, the results obtained from different commercial software packages can vary widely [57]. Recently, it has been shown that there is no change in patient outcomes when the usage of CTP studies is significantly reduced in the evaluation of acute stroke patients [59].

MRI studies represent an alternative pathway for the workup of acute stroke patients. Noncontrast MRI with susceptibility-weighted sequences is likely to be as sensitive as noncontrast head CT scans in the detection of intracranial hemorrhage [62,63]. However, routine gradient-recalled echo (GRE) studies are unlikely to be similarly sensitive in the detection of ICH [62]. SWI is, however, very sensitive to patient movement and therefore may not be able to entirely eliminate noncontrast head CT in acute stroke patients. The greatest value of MRI at present lies in the information provided by DWI in patients presenting with AIS. The extent of infarcted tissue present on DWI has been shown to have a direct correlation with poor outcomes in stroke patients. In general, if a large core infarct volume (>70 mL) is found on DWI, IAT should not be attempted given the low likelihood of good outcome [64,65]. The risk of hemorrhagic conversion of infarcted brain tissue following IV-tPA administration also increases with increased volume of tissue with restricted diffusion [66]. MRA can be used in a fashion analogous to CTA for the identification of arterial obstruction from thrombosis. In addition, the length of the clot found on MRA or CTA appears to have inverse correlation with the success of reperfusion strategies [67].

MR perfusion can be obtained rapidly and several studies have demonstrated the value of determining the ischemic penumbra in patients presenting with AIS using the diffusion/perfusion mismatch [25,64,68,69]. MR perfusion, similar to CTP, suffers from low signal-to-noise ratio and sensitivity to patient movement. Additionally, concerns regarding usage of gadolinium-based contrast agents are likely to make it unavailable for patients with renal impairment. These drawbacks in the use of perfusion imaging have led to the development of a clinical/diffusion mismatch algorithm in the management of AIS patients [59,70]. A clinically significant clinical/diffusion mismatch indicating an ischemic penumbra is demonstrated by an NIHSS >10 and a DWI lesion <70 mL [59,70]. Patients who present with such a significant mismatch may then be candidates for IV or IAT.

Variant 4: New focal neurologic defect, fixed or worsening. Longer than 6 hours. Suspected stroke.

The time period since symptom onset in this variant has changed since the last version of the ACR Appropriateness Criteria on cerebrovascular disease. In the previous version, the variants of new focal neurologic deficit included time windows of <3 hours, 3–24 hours, and >24 hours since symptom onset. A major factor in determining the previous time windows was the FDA-approved time window of <3 hours for treatment of acute stroke with IV-tPA. However, recently the data from multiple randomized endovascular studies have shown that patients with large-vessel occlusion (ICA terminus or MCA, M1 segment) who undergo endovascular treatment within 6 hours from symptom onset for anterior circulation AIS do indeed have significantly better outcomes when compared to patients who are treated with IV-tPA alone [2-5]. Therefore, the new variants include time windows of <6 hours and >6 hours.

When the patient presents with stroke beyond the therapeutic window of 6 hours since symptom onset, further evaluation is ideally performed with a contrast-enhanced brain MRI along with TOF-MRA of the circle of Willis and CE-MRA of the cervical vessels. If there is concern for carotid artery dissection, axial fat-suppressed T1-weighted images through the neck should be obtained. An example of a stroke-protocol MRI includes a contrast-enhanced brain MRI with sequences including DWI, ADC, T1, T2, FLAIR, T2* or SWI, and postcontrast T1-weighted images, as well as TOF-MRA of the circle of Willis and CE-MRA of the cervical vessels. This combination of sequences allows for identification of other causes for the patient's symptoms and allows the estimation of the age of the infarct. Hyperacute infarct (0–6 hours) will demonstrate restricted diffusion only, which represents cytotoxic edema. Acute infarct (6 hours–3 days) will demonstrate restricted diffusion (cytotoxic edema) and hyperintensity on FLAIR/T2 images (vasogenic edema). Subacute infarct (3–14 days) is characterized by gyral contrast enhancement and is the time period when hemorrhagic transformation is most likely to occur. Vasogenic edema also peaks during the subacute time period at around 5 days, putting the patient at risk for herniation. Restricted diffusion usually resolves during the subacute period. Chronic infarction (>2 weeks) is characterized by volume loss after dead neuronal tissue is removed and replaced by gliosis with subsequent cystic encephalomalacia. In patients with hemorrhage or hemorrhagic conversion of ischemic stroke, the changes in appearance of blood products over time on T1- and T2-weighted MR sequences are well documented. NCCT and CTA can alternatively be performed if there is contraindication to MRI. However, CT is significantly less capable of providing information regarding the acuity of findings. The role of perfusion imaging in this scenario is currently unclear and in question given the low signal-to-noise ratio, low contrast-to-noise ratio, high sensitivity to patient motion, high interobserver variability, and high intervendor software variability. CTP may play a role to

evaluate for ischemia when MRI is contraindicated or cannot be performed. Additionally, CTP has shown some promise in identifying patients who may benefit from therapy outside the accepted treatment window [71-74].

Variant 5: Risk of unruptured aneurysm, including patients with polycystic kidney disease, patients who have at least two first-degree relatives with history of subarachnoid hemorrhage (SAH), and those with previously ruptured and treated aneurysms.

Screening for unruptured intracranial aneurysms in the general population is neither recommended nor feasible given the lack of evidence for treatment of all incidentally discovered aneurysms and the high prevalence of aneurysms in the general population. However, screening for intracranial aneurysms may be appropriate in specific patient subgroups such as those with polycystic kidney disease, patients who have at least 2 first-degree relatives with history of SAH, and those with previously ruptured and treated aneurysms. Although conventional angiography remains the gold standard in aneurysm diagnosis, it is not an appropriate screening test given its invasiveness, except in patients who have had previous aneurysm treatments. DSA, compared with noninvasive imaging alternatives, is least likely to be affected by artifacts from prior treatment. MRA and CTA are noninvasive imaging alternatives. MRA is an excellent screening modality given its lack of ionizing radiation and the lack of need for IV contrast. CTA has superior spatial resolution compared with MRA and is not susceptible to artifacts due to slow flow and turbulence. However, CTA exposes the patient to radiation and requires the use of IV contrast, which may not be feasible in patients with contrast allergy or poor kidney function. A few studies have demonstrated the feasibility of MRA for use in screening for aneurysms in high-risk patients [75,76]. CTA has been shown to detect aneurysms with overall sensitivities of 85%–95%. However it has difficulty detecting small aneurysms <3 mm, and the sensitivities are around 50% for these smaller aneurysms [77,78]. MRA has also been shown to have difficulty with aneurysms <3 mm in size [79]. Overall, MRA and CTA likely have comparable sensitivities in the detection of intracranial aneurysms, although MRA likely has slightly inferior specificity, with no significant differences in the performances of contrast-enhanced and noncontrast MRA examinations.

Variant 6: Clinically suspected acute SAH, not yet confirmed.

SAH accounts for only 3% of all strokes. However, it affects young patients, with half being younger than 55, and it has a high mortality rate of around 50% [80]. The most common presentation of nontraumatic SAH is sudden onset of severe headache; however, patients may present with decreased level of consciousness, focal neurologic deficit, meningismus, nausea, seizure, or low back pain. NCCT remains the initial imaging test of choice to evaluate for suspected SAH because of its high sensitivity for acute hemorrhage, wide availability on a 24-hour basis, lack of absolute contraindications, speed of image acquisition, and ease of patient monitoring. The very high initial sensitivity of noncontrast head CT for SAH declines progressively with time, and in these situations, MRI with FLAIR, SWI, or T2* GRE can be useful [63,81,82]. Noncontrast MRI with susceptibility-weighted sequences is likely to be as sensitive as noncontrast head CT scans in the detection of intracranial hemorrhage [62,63]. However, routine GRE studies are unlikely to be similarly sensitive in the detection of ICH [62]. SWI is, however, very sensitive to patient movement. Therefore, noncontrast head CT remains the gold standard in patients who present with acute symptoms. Care should be taken when evaluating intracranial hemorrhage on MRI since it can appear heterogeneous, depending on the pulse sequence, magnet field strength, location, and oxidative state of hemoglobin and character of its subsequent breakdown products. The changes in appearance of blood products over time on T1- and T2-weighted MR sequences are well documented. Once SAH is identified, further evaluation described in Variant 7 can include vascular imaging, which may consist of catheter angiography, CTA, or MRA.

Variant 7: Proven SAH by lumbar puncture or imaging.

If nontraumatic SAH is detected on NCCT or by lumbar puncture, a search for a cerebral aneurysm should begin since aneurysm rupture is responsible for 80%–90% of all nontraumatic SAHs [83]. Catheter arteriography remains the gold standard in aneurysm evaluation, with sensitivity >90% which falls to slightly greater than 80% in the setting of acute SAH [84,85]. CTA has been shown to detect aneurysms with overall sensitivities of 85%–95%. However, the sensitivity of CTA for smaller aneurysms (<3 mm in diameter) is much lower, at around 55% [77,78,86,87]. Likewise, the sensitivity of CTA is also lower in the setting of diffuse SAH [88]. These limitations are important to recognize since very small aneurysms (<3 mm in diameter) can account for almost a third of ruptured aneurysms [89]. Therefore, although CTA is increasingly being used as the sole vascular imaging study prior to treatment [90,91] at present, catheter angiography remains the gold standard. The negative predictive

value of CTA in this setting is poor and the performance of catheter angiography in SAH patients with a negative CTA study can result in the detection of a causative lesion in 15% of those with diffuse SAH and 9% of those with sulcal SAH [92,93]. It is however, likely that recent advances in CTA will eventually lead to CTA supplanting DSA as the test of choice at some point in the future. The use of 3-D rotational angiography during catheter angiography is recommended due to the higher sensitivity of this technique as well as the ability of 3-D images to depict the relationship of the aneurysm to the parent vessel and adjacent arterial branches [94]. MRA is likely as sensitive as CTA in the diagnosis of intracranial aneurysm. However, its specificity may be slightly inferior to that of CTA [79]. The speed and ready availability of CTA make it a more feasible noninvasive imaging modality in the acute setting. However, unlike CTA, which requires IV contrast, MRA of the head does not require the use of IV contrast and can be useful in patients with renal dysfunction or iodine allergy. MRA, similar to CTA, can have difficulty identifying aneurysms <3 mm. If an intracranial cause of nonperimesencephalic SAH cannot be found, vascular imaging of the neck, such as CTA, MRA, or DSA, may be useful to evaluate for less common causes of SAH in the neck, such as arterial dissection, spinal AVM or AVF, or spinal artery aneurysm.

Variant 8: Proven SAH, negative angiogram, follow-up.

Initial catheter arteriography can be negative in 10%–20% of cases of aneurysmal SAH because of small aneurysm size, aneurysm thrombosis, local vasospasm, or incomplete study. A large meta-analysis showed that when these patients undergo repeat diagnostic catheter angiography, a causative anomaly can be found in about 10% of cases [95]. However, rather than await a repeat diagnostic catheter angiography study, it is recommended that these patients undergo noninvasive imaging with CTA or MRA (if these had not been performed until this stage) [96,97]. When both initial catheter angiography and noninvasive studies are negative in patients with nonperimesencephalic SAH, catheter angiography should still be repeated at 1–2 weeks [98]. If an intracranial cause of nonperimesencephalic SAH cannot be found, vascular imaging of the neck such as CTA, MRA, or DSA, may be useful to evaluate for less common causes of SAH in the neck, such as arterial dissection, spinal AVM or AVF, or spinal artery aneurysm.

Variant 9: Asymptomatic or no new symptoms. Follow-up imaging of previously treated cerebral aneurysms.

Previously treated aneurysms can show growth or recurrent aneurysmal sac filling. The rates of aneurysm growth and recurrence vary depending upon the technique used for aneurysm treatment, such as coil embolization, stent-assisted coil embolization, clipping, or flow diversion. Definitive follow-up evaluation for residual filling of previously treated aneurysms is performed by catheter arteriography and this remains the gold standard.

However, MRA has shown significant promise in the follow-up of patients with previously treated ruptured aneurysms [99] and should be considered in patients who are considered to be high risk for repeated diagnostic angiography or in patients in whom the significance of a small residual or recurrent aneurysm is debatable, such as those with poor baseline function or older patients [100,101]. A systematic review and meta-analysis has shown that both TOF-MRA and CE-MRA have moderate to high diagnostic performance in the follow-up of previously coiled aneurysms [102]. For patients in whom MRA is contraindicated, CTA may offer a noninvasive alternative, particularly in patients with clipped aneurysms. However, CTA is severely limited by metal artifact in the evaluation of aneurysms previously treated with platinum coils. Flow diverters are very infrequently used in the treatment of ruptured aneurysms and the best noninvasive imaging modality for follow-up in these aneurysms is currently not known [103]. In the case of patients with unruptured aneurysms that have been treated with flow diverters, DSA remains the study of choice.

Vascular imaging is the main focus when following up treated aneurysms. However, parenchymal imaging can be useful in certain clinical scenarios, including treated giant aneurysms, which can cause significant surrounding edema, and posterior fossa aneurysms which can cause hydrocephalus. When deciding whether to perform CT or MRI for parenchymal imaging, it may be easiest to perform the same parenchymal imaging modality as the vascular imaging modality (CT with CTA and MRI with MRA), keeping in mind that MRI has superior soft-tissue contrast resolution and higher sensitivity for acute infarction compared to CT.

Variant 10: Asymptomatic or no new symptoms. Follow-up imaging of untreated cerebral aneurysms.

Unruptured aneurysms, which are incidentally discovered on vascular imaging (CTA, MRA, DSA), are best followed up using the same vascular imaging modality (CTA, MRA, DSA) on which the initial diagnosis was

made. Follow-up of unruptured aneurysms is important due to the higher risk for rupture in aneurysms that show interval growth on noninvasive imaging studies [104]. If the aneurysm appears stable after multiple repeated studies on CTA or DSA, it may be reasonable to switch to MRA for further follow-up in order to reduce ionizing radiation dose to the patient. Other imaging techniques for risk stratification in unruptured arterial aneurysms, such as computational flow dynamic studies [105], are yet to be standardized or understood, and these are not currently recommended for clinical decision making.

Vascular imaging is the main focus when following up untreated aneurysms. However, parenchymal imaging with CT or MRI may be useful in certain scenarios, including the evaluation of thrombosed or partially thrombosed aneurysms, the relationship of the aneurysm to the dura, and to search for the presence of calcification. When deciding whether to perform CT or MRI for parenchymal imaging, it may be easiest to perform the same parenchymal imaging modality as the vascular imaging modality (CT with CTA and MRI with MRA), keeping in mind that MRI has superior soft-tissue contrast resolution and higher sensitivity for acute infarction and hemosiderin deposition compared to CT. However, CT is more likely to demonstrate aneurysm wall calcification.

Variant 11: Evaluation for cerebral vasospasm after aneurysmal SAH.

Cerebral vasospasm occurs in up to 70% of patients after aneurysmal SAH and is a major cause of morbidity and mortality in those affected. The onset is usually at 3–5 days after hemorrhage, with maximal vessel narrowing at 5–14 days and resolution after 2–4 weeks [106]. Cerebral vasospasm is responsible for approximately 50% of deaths in patients who survive the initial SAH [106]. Imaging findings in vasospasm often precede clinical findings and represent an opportunity to guide treatment to prevent permanent neurologic sequelae [107]. However, only 50% of patients with vasospasm on imaging develop clinical symptoms, and this discrepancy may be in part due to adequate collateral circulation [106]. Conventional angiography is the gold standard imaging test to evaluate for cerebral vasospasm. However, it is not a proper screening test given its invasiveness and potential complications. Transcranial Doppler (TCD) is a widely used screening modality for vasospasm because it is an accurate, sensitive, noninvasive, low-cost imaging test without radiation exposure to the patient that can be done at the patient's bedside and can be performed daily to evaluate for vasospasm or to follow response to treatment [108-110]. However, TCD is operator dependent and an acoustic window may not be available to evaluate the intracranial vasculature in some patients.

CTA, MRA, and perfusion imaging may also be useful in the evaluation of cerebral vasospasm. The ideal indication for CTA in the evaluation for cerebral vasospasm may be in the setting of indeterminate TCD with clinical findings suggestive of vasospasm [111]. In a meta-analysis including studies of mostly symptomatic patients, CTP and CTA demonstrated high diagnostic accuracy in the evaluation of cerebral vasospasm [112]. Although CTA and MRA may demonstrate luminal narrowing, perfusion imaging with CT or MR may add important information since patients with luminal narrowing may have normal perfusion secondary to adequate collateral flow. However, when considering multiple sequential imaging studies, it is important to be aware of the risks and benefits, being mindful of contrast and radiation dose to the patient.

Parenchymal brain imaging may be useful in symptomatic patients to evaluate for and follow-up cerebral infarcts and to investigate changes in the patient's clinical status with equivocal TCD and angiographic findings. Parenchymal brain imaging is ideally performed with MRI because of its superior soft-tissue contrast resolution and its high sensitivity for acute infarct. CT can be performed for parenchymal brain imaging if there is a contraindication to MRI. However, CT is less sensitive than MRI for acute infarct. IV contrast can help identify subacute infarcts because they characteristically enhance with contrast.

Variant 12: Clinically suspected parenchymal hemorrhage (hematoma), not yet confirmed.

NCCT remains the initial imaging test of choice to evaluate for hemorrhage in patients presenting with stroke symptoms because of its high sensitivity for acute hemorrhage, wide availability on a 24-hour basis, lack of absolute contraindications, speed of image acquisition, and ease of patient monitoring. Noncontrast MRI with susceptibility weighted sequences is likely to be as sensitive as noncontrast head CT scans in the detection of intracranial hemorrhage [62,63]. However, routine GRE studies are unlikely to be similarly sensitive in the detection of ICH [62]. SWI is, however, very sensitive to patient movement. Therefore, noncontrast head CT remains the gold standard in acute stroke patients. Care should be taken when evaluating intracranial hemorrhage on MRI since it can appear heterogeneous, depending on the pulse sequence, magnet field strength, location, and

oxidative state of hemoglobin and character of its subsequent breakdown products. The changes in appearance of blood products over time on T1- and T2-weighted MR sequences are well documented. Further imaging with contrast-enhanced MRI or CT as well as MRA, CTA, MRV, or CTV can be considered once hemorrhage is detected and there is concern for underlying mass or vascular pathology. This is discussed further in Variant 13.

Variant 13: Proven parenchymal hemorrhage (hematoma).

There are numerous possible etiologies for cerebral intraparenchymal hemorrhage including hypertension, amyloid angiopathy, coagulopathy, AVM, cavernous malformation, neoplasm, dural venous sinus or cortical venous thrombosis, and dural AVF. If the original noncontrast head CT and clinical history strongly point to a hypertensive cause (basal ganglia location of hemorrhage, patient age >55 years, clinical history of hypertension), it may be reasonable to limit further imaging workup to include follow-up serial imaging studies with noncontrast head CT to evaluate for hemorrhage expansion, herniation, hydrocephalus, and other complications that may require surgical intervention. However, if the etiology of the parenchymal hemorrhage remains in question after initial imaging, further investigation with brain MRI without and with contrast is the imaging study of choice. An example of a brain MRI without and with contrast protocol includes T1, T2, FLAIR, DWI, T2* or SWI, and postcontrast T1-weighted images. If there is concern for a vascular malformation, then MRA of the head should also be performed. MRA can be performed without or with contrast, although contrast-enhanced brain MRA tends to have significant venous contamination. Time-resolved MRA techniques may help identify associated arterial and venous anatomy. MRV of the head may also be useful to help characterize venous drainage in AVMs and dural AVFs. MRV of the head in this situation is best performed with and without contrast. The evaluation for high-flow vascular malformations including AVMs and dural AVFs is further described in Variant 14. Additionally, if there is concern for CVT, then venous imaging should be performed. The imaging evaluation of CVT is described in Variant 15. Vascular imaging of the neck with MRA and MRV in conjunction with vascular imaging of the head may be useful to evaluate the anatomy, patency, and involvement of the neck vasculature in the initial imaging workup. However, follow-up imaging of the lesion responsible for the parenchymal hemorrhage is often adequately performed with head-only vascular imaging. CE-MRA of the neck is superior to noncontrast MRA due to the difficulties that noncontrast MRA has evaluating the carotid bifurcations and great-vessel origins.

If there is a contraindication to MRI or it is unavailable, then imaging with CT can be utilized, keeping in mind that CT has inferior soft-tissue contrast resolution compared to MRI. CTA and CTV can be utilized for the vascular imaging workup. However, they utilize radiation and require IV contrast, whereas TOF-MRA/MRV and PC-MRA/MRV can be done without contrast or exposure to radiation. Contrast-enhanced head CT can be performed after noncontrast head CT for parenchymal evaluation and possible identification of enhancing neoplasm/metastases. Active bleeding demonstrated by extravasation of contrast in the hematoma on head CTA or contrast-enhanced head CT, known as the "spot sign," can predict risk of hematoma expansion and risk of in-hospital mortality and poor outcome [113,114]. Subsequent serial follow-up imaging for parenchymal hemorrhage is usually performed with noncontrast head CT to evaluate for hematoma expansion, herniation, hydrocephalus, and other complications that may require surgical intervention.

Nonaneurysmal vascular malformations of the brain can be divided into low-flow and high-flow malformations. High-flow vascular malformations are AVMs and dural AVFs and their imaging evaluation is further described in Variant 14. Low-flow vascular malformations consist of developmental venous anomalies (DVAs) with or without associated cavernomas. DVAs are by themselves benign lesions, that are easily detected on the basis of a pathognomonic medusa-head appearance on CTA or MRA [115-117]. Cavernomas, which are sometimes associated with DVAs, can present with intracranial hemorrhage [118,119]. Cavernomas are best diagnosed by noninvasive imaging, particularly with SWI [117,120]. DSA is not recommended for the evaluation of either abnormality except to rule out rare arterialized DVAs. Atypical DVAs are also easily evaluated with SWI, and do not require DSA [116,120,121].

Variant 14: Evaluation of high-flow vascular malformations.

High flow vascular malformations include AVMs and dural AVFs. AVMs are pial high-flow vascular malformations that are thought to be congenital in origin. They may be asymptomatic and discovered incidentally or they may present with parenchymal hemorrhage, seizures, or headache [122,123]. Imaging studies for AVMs should enable assessment of the malformation's arterial feeders, nidus, venous drainage, location, and relationship to adjacent eloquent brain structures [122,124]. The Spetzler-Martin AVM grading system uses 3 imaging

features of the AVM to determine surgical risk, including 1) determination of the size of the AVM, 2) the relationship of the AVM to eloquent brain cortex, and 3) determination of superficial versus deep venous drainage of the AVM. In the case of patients who are being evaluated for a suspected AVM in the absence of intraparenchymal hemorrhage, MRI of the brain with CE-MRA/venography or dynamic MRA/venography is likely to provide the maximum information. Several 4-D MRA/venography techniques are available, all of which at present have a tradeoff between spatial and temporal resolution [125,126]. Parenchymal brain imaging utilizing brain MRI with and without contrast is helpful in evaluating the location of the AVM in relation to eloquent brain tissue and can be useful in evaluating for prior hemorrhage within the AVM, both important prognostic factors. Alternatively, head CT without and with contrast may be used for parenchymal brain evaluation if MRI cannot be performed; however, CT has inferior soft-tissue contrast resolution compared to MRI and is not as sensitive for prior micro-hemorrhages. In patients in whom MRI is contraindicated, CTA/venography can be useful. Subsequent evaluation of AVMs requires DSA to accurately document hemodynamics, identify nidal or juxtanidal aneurysms, and to identify fistulous regions within the nidus. Vascular imaging of the neck with MRA and MRV when performed in conjunction with vascular imaging of the head may be useful to evaluate the anatomy, patency, and involvement of the neck vasculature in the initial imaging workup. However, head-only vascular imaging may often be adequate for follow-up imaging of the AVM or dural AVF. CE-MRA of the neck is superior to noncontrast MRA due to the difficulties that noncontrast MRA has at the carotid bifurcations and great-vessel origins.

Although there have been rapid advances in dynamic MRI, at present DSA still remains the imaging study of choice for detailed investigation of AVMs. In patients who present with hemorrhage, DSA is the study of choice [124]. If possible, DSA should be delayed until the edema from the hemorrhage has subsided. The sensitivity of MR and CT imaging for small AVMs is poor, especially in the setting of hemorrhage [124].

Follow-up of AVMs can be performed with noninvasive imaging, preferably MRI [124]. Caution must be exercised in interpretation of these images since draining veins can still remain dilated on MRA/MRV studies of treated AVMs even in the absence of arteriovenous shunting. SWI could be useful in this setting [121,127]. Arterial spin labeling with selective arterial excitation shows great promise but is not yet mainstream when it comes to the detection and characterization of AVMs [13]. Phase-contrast imaging, also not yet mainstream, may be useful in the evaluation of AVMs, allowing for hemodynamic measurements [128].

DSA can be performed if there is concern regarding the accuracy of MRI findings, particularly in the follow-up of patients who have undergone surgical resection of AVMs. CTA can be significantly affected by the presence of embolic material or surgical clips and is in general not very useful for the follow-up of treated AVMs.

Dural AVFs are rare lesions, that are thought to be acquired. They are often asymptomatic but they can present with pulsatile tinnitus, headaches, seizures, or hemorrhage. The management of dural AVFs depends on depiction of arterial feeders and accurate grading, which require clear depiction of draining veins [9]. Dural AVFs are often located close to the inner table of the cranium or near the skull base, rendering their detection and characterization by noninvasive imaging a challenging proposition. Indirect signs on noninvasive vascular imaging (CTA and MRA) such as “shaggy sinus sign” [129] or cortical venous dilation in the absence of venous sinus thrombosis or parenchymal nidus [130] can give the practitioner a clue to the presence of dural AVFs. However, DSA remains the gold standard for detection, grading, and treatment planning for dural AVFs. Recent advances in 4-D MRA with time-of-arrival maps as well as the utilization of arterial spin labeling techniques shows promise in noninvasive characterization of dural AVFs [8-12].

Variant 15: Suspected dural venous sinus thrombosis.

CVT is an uncommon cause for stroke, affecting only about 1%–2% of stroke patients [131]. The patients can present with headaches, seizures, or decreased level of consciousness from ischemic or hemorrhagic stroke [131]. Accurate diagnosis is important since treatment can significantly improve outcomes.

The imaging evaluation for CVT can vary upon the acuity of the patient presentation and the availability of imaging technology. In the acute presentation, NCCT is often performed initially to evaluate for intracranial causes requiring immediate intervention. Signs of CVT on NCCT, including a dense dural venous sinus or cortical vein, are unreliable due to changes in clot density over time as well as hemoconcentration or hemodilution. In fact, NCCT is abnormal in only 30% of patients with CVT [131]. These changes in density of the thrombus can also cause difficulty in visualizing the classic “empty delta” sign of a central filling defect from

thrombus within the venous sinus on contrast-enhanced CT. If there is suspicion for CVT after the initial NCCT is performed in the acute setting, CTV can be quickly performed while the patient is still on the CT scan table. In a less acute setting or an acute setting where MRI is readily available without contraindications, contrast-enhanced brain MRI and MRV are often performed for optimal evaluation.

Although CTV may be as accurate as MRV in the diagnosis of CVT [132], both techniques have their advantages and disadvantages. CTV requires the use of IV iodinated contrast, limiting its use in patients with acute or severe chronic renal failure. TOF and PC-MRV do not require IV contrast and can be used in patients with renal dysfunction. CTV exposes the patient to radiation, and therefore MRV should alternatively be considered in children in order to reduce radiation exposure in this radiation-sensitive population. However, sedation may be required for some children or claustrophobic patients undergoing MRV. CTV is less prone to image degradation due to patient motion than MRV. 3-D reconstruction can be limited in CTV due to difficulty removing bone adjacent to the cerebral dural venous sinuses.

MRI evaluation for CVT optimally consists of brain MRI with and without contrast along with brain MRV with and without contrast. Noncontrast brain MRI may be able to visualize CVT depending on the age of the thrombus, similar to visualizing the evolution of a hematoma on MRI. Brain MRI with and without contrast is useful in evaluating for complications of CVT, including venous infarction, hemorrhage, and edema. Contrast-enhanced brain MRI is useful for determining the age of an infarct, if present, as well as evaluating for other causes of the patient's symptoms, such as tumor or infection. Brain MRV is ideally performed with and without IV contrast. Noncontrast MRV techniques include 2-D TOF, 3-D TOF, and phase-contrast. Both 2-D and 3-D TOF MRV are limited when there is T1 hyperintense thrombus, which can mimic normal flow. 3-D TOF MRV is limited in areas of slow and turbulent flow which can cause signal loss mimicking thrombus. However, a postcontrast 3-D TOF MRV may help with problem solving in this situation. PC-MRV does not have difficulty evaluating slow flow or differentiating thrombus from normal venous flow. Postcontrast MRV is not limited by slow flow, but T1-hyperintense thrombus may mimic normal flow, so it is important to also evaluate the noncontrast brain MRI and MRV for complete characterization. Subtraction images can also be helpful for the postcontrast MRV to remove the T1-hyperintense thrombus from the MRV images.

Given the current noninvasive imaging options, including MRV and CTV, invasive imaging with catheter venography is seldom needed and can be reserved for when noninvasive imaging options are unavailable or for treatment purposes. Imaging of the neck with MRV, CTV, DSA, or even US may be useful to evaluate the extent of thrombus in the neck. The role of perfusion imaging in this scenario is currently unclear and in question given the low signal-to-noise ratio, low contrast-to-noise ratio, high sensitivity to patient motion, high interobserver variability, and high intervendor software variability. However, there have been studies of perfusion imaging showing some promise in the evaluation of CVT, possibly revealing prognostic information and allowing for evaluation of an ischemic penumbra [133].

Variant 16: Central nervous system vasculitis.

Central nervous system (CNS) vasculitis represents a heterogeneous group of disease processes resulting in inflammation and destruction of the CNS vasculature. The clinical presentation is highly variable and includes ischemic stroke, hemorrhagic stroke, seizure, migraine, psychiatric disease, and cognitive decline. CNS vasculitis is a significant cause of stroke, especially in younger patients, with over half of ischemic strokes in children caused by arteriopathy [134,135]. CNS vasculitis may be confined to the CNS in primary angiitis of the CNS (PACNS) or may be part of a systemic vasculitis secondary to numerous other causes including autoimmune and infectious etiologies. PACNS is rare with an estimated average annual incidence of 2.4 cases per 1 million person-years [136,137]. Vasculitides in general are commonly classified according to the size of the vessels involved, including small-vessel (antineutrophil cytoplasmic autoantibody-associated and immune complex vasculitis), medium-vessel (polyarteritis nodosa and Kawasaki disease), and large-vessel vasculitis (Takayasu and giant cell arteritis) [138]. Timely and accurate diagnosis is important to prevent permanent neurologic sequelae and to guide treatment.

Imaging plays a key role in the evaluation for CNS vasculitis; however, biopsy currently remains the gold standard for diagnosis. Direct imaging findings of CNS vasculitis include vessel wall enhancement and thickening, and indirect imaging findings include vessel narrowing, dilation, occlusion, and a beaded appearance

as well as scattered nonspecific white-matter T2 hyperintensities on MRI, scattered infarcts in different vascular territories, perfusion defects, and hemorrhage.

Contrast-enhanced MRI and MRA of the head and neck (TOF-MRA of the circle of Willis and CE-MRA of the neck vasculature) are the initial imaging studies of choice in the evaluation for CNS vasculitis. MRI has unmatched soft-tissue contrast resolution to evaluate for indirect signs of vasculitis in the brain parenchyma, including scattered infarcts in different vascular territories (seen in 33% of cases) as well as scattered nonspecific white-matter T2 hyperintensities (seen in 42% of cases) [139]. However, scattered white-matter T2 hyperintensities are nonspecific and can be seen in multiple disease processes [140]. High-resolution contrast-enhanced MRI at 3T can be used to evaluate for direct signs of vasculitis, including wall thickening and enhancement in large- and medium-sized vessels [141,142]. Although still investigational, high-resolution CE-MRI at 7T may eventually allow evaluation of even smaller vessels [142]. MRA is still not as sensitive as conventional angiography in visualizing changes of vasculitis including vascular narrowing, dilation, and occlusion [143].

Therefore, if MRA is negative and vasculitis is still suspected, conventional angiography should then be performed. Small-vessel vasculitis changes are below the resolution of angiography and MRA and patients with small-vessel vasculitis usually have normal MRA and angiographic studies. Although conventional angiography remains the gold standard for imaging of vascular narrowing, dilation, or occlusion in CNS vasculitis, it is still relatively insensitive in the detection of biopsy-proven PACNS, with a sensitivity of 60% [144,145]. CT and CTA of the head and neck can be performed to evaluate for CNS vasculitis if there are contraindications to MRI and MRA; however, CT has inferior soft-tissue contrast resolution and is significantly less sensitive in visualizing changes in the brain parenchyma. However, noncontrast head CT can be useful to detect vasculopathy-related calcifications, such as in radiation/chemotherapy-related mineralizing microangiopathy. The use of perfusion imaging has been described in the evaluation of CNS vasculitis but is not commonly utilized [146]. US can also be used in the evaluation for extracranial vasculitis, including fibromuscular dysplasia and giant cell arteritis.

Summary of Recommendations

- Screening for carotid artery stenosis can be performed noninvasively with duplex US, CE-MRA, or CTA. The combination of duplex US and CE-MRA is a common choice for carotid artery evaluation. DSA is the gold standard for carotid artery evaluation and should be performed if noninvasive imaging is inconclusive or contradictory. Evaluation of cerebrovascular reserve with CT or MR perfusion with acetazolamide challenge may identify patients at higher risk for stroke due to poor collateral circulation.
- Imaging evaluation of TIA should be performed as soon as possible because of the associated high risk of future stroke and is ideally performed with contrast-enhanced brain MRI along with 3-D TOF-MRA of the circle of Willis and CE-MRA of the neck vasculature.
- Noncontrast head CT is the first-line imaging test for acute stroke patients to rule out intracranial hemorrhage and large infarct. When possible, CTA should be the next imaging study after IV-tPA administration in acute stroke patients to evaluate for large-vessel occlusion as a target for IAT. The role of CT and MR perfusion in acute stroke is presently unclear because of low signal-to-noise ratio, sensitivity to patient motion, and varied results between software packages, leading to a gradual decline in its usage, without a significant change in patient outcomes despite its decreased use. Core infarct volume demonstrated by DWI has been shown to predict outcomes in stroke patients, with core infarct volume >70 mL indicative of poor outcomes even with IAT. The importance of the ischemic penumbra in acute stroke has been demonstrated. However, CT and MR perfusion studies can be unreliable, leading to the development of a clinical/diffusion mismatch algorithm. A clinical/diffusion mismatch indicating an ischemic penumbra is demonstrated by a NIHSS >10 and a DWI lesion <70 mL.
- Patients presenting with acute stroke beyond the 6-hour treatment window are ideally evaluated with contrast-enhanced brain MRI along with 3-D TOF-MRA of the circle of Willis and CE-MRA of the neck vasculature. Age of the infarct can be determined with contrast-enhanced brain MRI.
- Patients with risk factors for cerebral aneurysms can undergo noninvasive screening with TOF-MRA or CTA. TOF-MRA does not require IV contrast and lacks ionizing radiation exposure to the patient. However, it may not be feasible in claustrophobic or morbidly obese patients and patients with cardiac devices or metal shrapnel. CTA has higher spatial resolution but requires IV contrast and exposes the patient to radiation.

- The initial imaging study in patients presenting with suspected nontraumatic intracranial hemorrhage, whether SAH or intraparenchymal hemorrhage, should be noncontrast head CT.
- Initial evaluation in patients with acute nontraumatic SAH could start with DSA or noninvasive imaging with CTA or MRA. If the initial DSA is negative, then CTA or MRA should subsequently be performed. If CTA or MRA was performed as the initial imaging test and was negative, then DSA should be performed for further evaluation. If both initial DSA and noninvasive studies are negative, DSA should be repeated in 1–2 weeks.
- Definitive imaging follow-up of treated aneurysms is performed with DSA. However, MRA has shown promise in the follow-up of previously treated aneurysms, whether CE-MRA or noncontrast TOF-MRA. CTA is a noninvasive imaging alternative. However, CTA is severely limited in the evaluation of previously coiled aneurysms by metal artifact.
- Unruptured aneurysms, that are incidentally discovered on noninvasive imaging are best followed up using the same noninvasive imaging modality on which the initial diagnosis was made.
- Definitive diagnosis of cerebral vasospasm after SAH is made with catheter angiography. Screening for vasospasm is performed with TCD US. CTA or MRA may be useful in the setting of indeterminate TCD. CT or MR perfusion may be beneficial since some patients with luminal narrowing may have normal perfusion partially due to adequate collateral circulation.
- Intraparenchymal cerebral hemorrhages which have the classic clinical history and imaging appearance indicative of hypertensive hemorrhage usually do not require further imaging workup other than follow-up noncontrast head CT to evaluate for hemorrhage evolution and complications.
- Intraparenchymal cerebral hemorrhages that do not have the classic clinical history and imaging appearance for hypertensive hemorrhage, should undergo further parenchymal and vascular imaging, ideally with contrast-enhanced brain MRI, MRA, and sometimes MRV. CT, CTA, and sometimes CTV are imaging alternatives.
- Evaluation of high-flow vascular malformations, including AVMs and dural AVFs, can begin with noninvasive imaging, utilizing MRI and MRA/MRV or, alternately, using CT and CTA/CTV. Brain parenchymal evaluation is ideally performed with contrast-enhanced brain MRI due to its superior soft-tissue contrast-resolution compared with CT. Noninvasive vascular imaging can be performed with either MRA/MRV or CTA/CTV depending on the availability of the imaging modality and after considering the risks and benefits of the use of IV contrast, ionizing radiation, and MRI safety issues. However, definitive characterization of AVMs and dural AVFs requires catheter angiography.
- Vascular imaging in the evaluation for CVT can be performed with either MRV or CTV and depends on the availability of the imaging modality and after considering the risks and benefits of the use of IV contrast, ionizing radiation, and MRI safety issues. MRV is ideally performed without and with IV contrast due to difficulties that noncontrast MRV has with slow and turbulent flow. CTV requires IV contrast administration and ionizing radiation exposure to the patient. Parenchymal brain imaging in the evaluation of CVT is ideally performed with contrast-enhanced brain MRI, as it is superior to head CT at detecting parenchymal brain complications of CVT including edema and infarct.
- In the evaluation of CNS vasculitis, CE-MRI and MRA of the head and neck are the initial imaging studies of choice to evaluate for vessel narrowing/dilation/occlusion of large- and medium-vessels, scattered white-matter T2 hyperintensities, and scattered infarcts in different vascular territories. High-resolution CE-MRI can be used to evaluate for direct signs of vasculitis including vessel wall thickening and enhancement in large- and medium-vessels. Conventional angiography remains the gold standard imaging study for evaluation of large- and medium-vessel narrowing, dilation, or occlusion in CNS vasculitis. Small-vessel abnormalities are below the resolution of MRI, MRA, CTA, and catheter angiography. CT and CTA can be performed to evaluate for CNS vasculitis if there are contraindications to MRI and MRA. However, CT has inferior soft-tissue contrast resolution and is significantly less sensitive in visualizing changes in the brain parenchyma.

Summary of Evidence

Of the 146 references cited in the *ACR Appropriateness Criteria® Cerebrovascular Disease* document, 111 are categorized as diagnostic references including 3 well designed studies, 20 good quality studies, and 25 quality studies that may have design limitations. Additionally, 26 references are categorized as therapeutic references

including 19 well designed studies and 2 good quality studies. There are 68 references that may not be useful as primary evidence. There are 9 references that are meta-analysis studies.

The 146 references cited in the *ACR Appropriateness Criteria® Cerebrovascular Disease* document were published from 1981-2016.

While there are references that report on studies with design limitations, 44 well designed or good quality studies provide good evidence.

Relative Radiation Level Information

Potential adverse health effects associated with radiation exposure are an important factor to consider when selecting the appropriate imaging procedure. Because there is a wide range of radiation exposures associated with different diagnostic procedures, a relative radiation level (RRL) indication has been included for each imaging examination. The RRLs are based on effective dose, which is a radiation dose quantity that is used to estimate population total radiation risk associated with an imaging procedure. Patients in the pediatric age group are at inherently higher risk from exposure, both because of organ sensitivity and longer life expectancy (relevant to the long latency that appears to accompany radiation exposure). For these reasons, the RRL dose estimate ranges for pediatric examinations are lower as compared to those specified for adults (see Table below). Additional information regarding radiation dose assessment for imaging examinations can be found in the ACR Appropriateness Criteria® Radiation Dose Assessment Introduction document.

Relative Radiation Level Designations		
Relative Radiation Level*	**Adult Effective Dose Estimate Range**	**Pediatric Effective Dose Estimate Range**
O	0 mSv	0 mSv
☢	<0.1 mSv	<0.03 mSv
☢☢	0.1-1 mSv	0.03-0.3 mSv
☢☢☢	1-10 mSv	0.3-3 mSv
☢☢☢☢	10-30 mSv	3-10 mSv
☢☢☢☢☢	30-100 mSv	10-30 mSv
*RRL assignments for some of the examinations cannot be made, because the actual patient doses in these procedures vary as a function of a number of factors (eg, region of the body exposed to ionizing radiation, the imaging guidance that is used). The RRLs for these examinations are designated as "Varies".		

Supporting Documents

For additional information on the Appropriateness Criteria methodology and other supporting documents go to www.acr.org/ac.

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