IV.1

CT Angiography of the Neck and Brain

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Introduction

The evolution of multidetector computed tomography (MDCT) has allowed the development and advancement of CT angiography (CTA). While the concept of carotid artery evaluation by CT was introduced by Heinz and others in 1984 [1, 2], it has taken recent technological advances to bring the current methods into practice. CTA of the neck is used primarily to assess the carotid vessels. As CTA slice thickness and rendering methods have improved, so has the accuracy of stenosis determination. More recently, CTA of the neck has become the standard for traumatic injury. Routine utilization of CTA for the evaluation of carotid and vertebral arteries is now the norm. The technique also has been successfully applied to the intracranial vasculature. Detection of cerebral aneurysms and other vascular diseases are readily identified.

This chapter will discuss CT techniques and contrast optimization of MDCT for CTA of the neck and brain and discuss the interpretation of the diseases commonly evaluated by this technique.

CT Technique

Obtaining great quality CTA of the neck and brain requires optimizing CT technique and acquisition. Thin-slice CT attained while the contrast bolus is present is the fundamental doctrine. While some CT parameters are vendor specific, there are general principles that apply [3]. The scan for neck CTA is set up from the aortic arch to the skull base or to 1 cm above the top of the dorsum sella if additional information is desired about intracranial circulation. Alternatively, the scan can extend to the vertex of the skull. From a practical standpoint, this combined approach is most often used. For CTA of the brain, the scan starts at the C2 level and goes to 1 cm above the dorsum sella or to the vertex. In order to evaluate a suspected vascular lesion more cephalad, such as in the case of an arteriovenous malformation (AVM), the volume covered needs to include this region, too. In most cases, a 20-cm field of view is used. This can be adjusted up or down as the situation warrants; however, use of a smaller field of view improves resolution. Patient chin position is adjusted to a neutral position since the scan is obtained at no gantry tilt, otherwise, the vasculature of the anterior head may be missed. Scanning from caudal to cephalad minimizes the contrast volume needed and venous opacification; however, it does risk producing a nondiagnostic scan if there is not sufficient contrast present.

Slice thickness directly determines resolution in the Z-axis. For neck CTA, use of slices in the 0.5- to 1.5-mm range provides adequate resolution and coverage. In general, for four- and eight-slice scanners, a thickness of 1 mm is used while in 16- and 64-slice scanners, the thinnest option is selected. This is due in large part to the overall detector configuration and length. Gantry rotation times have also decreased with newer scanner iterations. For neck CTA on a 4- or 8-slice scanner, a time of 0.7 s is typically used. For a 16-slice CT, 0.5 or 0.6 s is used while 0.4 s is used for 64-slice CT. This may be manufacturer specific. One interesting variant is a hybrid method. Since imaging a small vessel, such as the 3-mm in-plane middle cerebral artery (MCA), is different than the 5-mm transversely oriented proximal internal carotid artery (ICA), one can scan faster through the neck and then slow down for the circle of Willis where more resolution is needed. An example is to use 0.5-s scans through the neck with 1.0-s scans through the head. Pitch also has a significant impact on image quality. In general, keeping the pitch at about 1 provides a balance between coverage and resolution.

Historically, a tube voltage of 140 kVp was used for CT to minimize tube heating and maximize

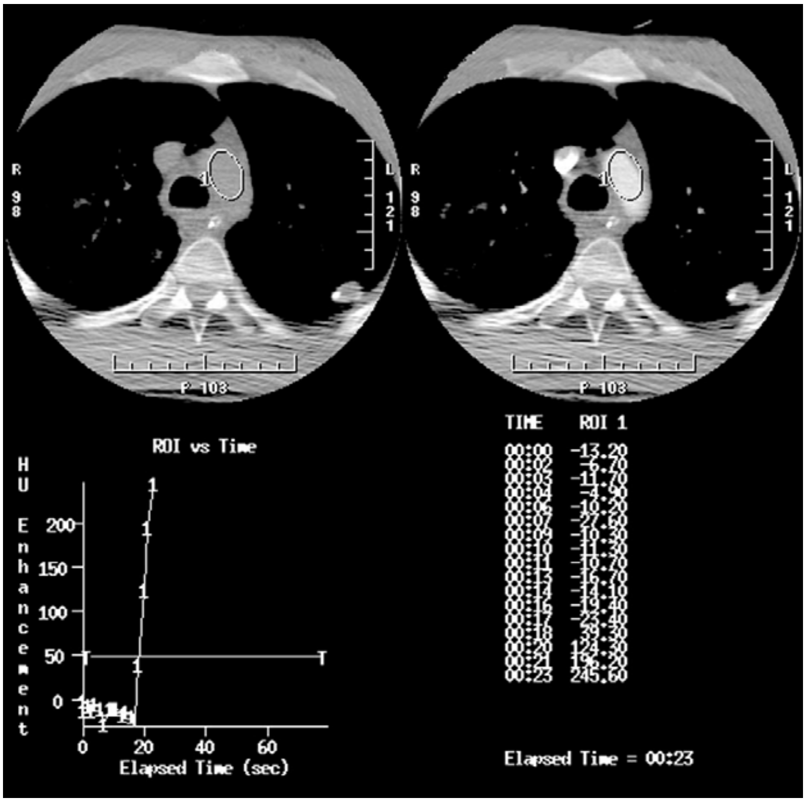


Fig. 1. Automatic triggering for CTA. The cursor is placed in the aorta, and sequential images are obtained during dynamic contrast injection. Scan commences when contrast density in Hounsfield units (HU) reaches a preset value of 50–100 or when the technologist visually sees sufficient opacity in the arteries. Note contrast enhancement versus time curve

tube life. However, one of the key advances of MDCT has been tube technology that improves heat unit dissipation and reliability. This has allowed the use of 120 kVp, which may improve relative opacification of contrast media. The tube load used depends on gantry speed, patient weight and size, and region scanned. In general, the milliampere second (mAs) used should be in the 220–260 range for an average adult patient. For a gantry rotation of 0.7 s, a 380-mA tube load is an acceptable starting point. The newer 16- and 64-slice scanners offer automatic mA adjustments based on in-plane and Z-axis attenuation. A range of mA is set, along with an image quality desired. For CTA of the brain, image quality needs to be set higher with lower noise. Neck studies permit a slightly higher noise setting.

In CT venography (CTV), the basic premise is that the contrast bolus needs to fill the major veins. CT parameters are adapted from CTA protocols. The field of view needs to include the entire head; 22 cm is suggested. For the 4-slice scanner, 2.5 mm slices may be used to provide coverage. Slice thickness of 1.25 mm is used in eight-slice scanners, which may be reduced to thinner slices on the 16- and 64-slice MDCT. Pitch may be increased to about 1.5. Less radiation is needed since the vessels are larger. Tube load and gantry rotation is adjusted for mAs of about 220, with gantry rotation of 0.7–0.8 s.

Contrast Optimization

Contrast timing is a key determinant of CTA image quality. Peak contrast opacification should occur at the time of the scan for each region evaluated. For the neck and brain, the use of high-concentration contrast optimizes visualization of small vessels and defines vessel boundaries for improved accuracy. It permits high iodine flux at an acceptable IV injection rate. Higher IV injection rates provide high iodine flux but at a greater risk of extravasation from the IV site. We typically use 4 ml/s in our patients. Ideally, the bolus of contrast only needs to be present for the length of time that is needed to scan the area of concern, offset by the time it takes to get to the artery of interest. In practice, it is difficult to always reliably time the contrast bolus. An arbitrary injection time of 15 s for the neck or 18 s for the brain might be in error due to poor cardiac output or arterial or venous stenosis. Anxious individuals or trauma patients may have a very rapid transit time due to increased cardiac output.

Bolus tracking and automatic triggering methods have improved with MDCT technology. For neck CTA, the aortic arch with a 500 HU trigger provides a good basis for beginning to scan (Fig. 1). Volume of contrast needed reflects the speed of the scanner, with 100 ml of contrast media needed for four- and eight-slice scanners and

75 ml needed for 16-slice scanners. For brain CTA, ideally, a 100 HU trigger at the distal cervical ICA is used. However, identification of this vessel can prove elusive in some patients, so the aortic arch trigger point can be used with an additional 2–3 s delay added. Contrast requirements for brain CTA is 50 ml for 16-slice and 75 ml for 4- and 8-slice scanners.

Image Processing

The acquired images are checked for adequacy at the scanner and then postprocessed. In the case of 16-slice scanners, the very thin slices are usually reconstructed at a thicker slice thickness of 1 mm. This reduces image noise and number of slices to review while permitting improved three-dimensional (3-D) images and reformation of the thinner slices due to isotropic pixel acquisition. There can be a substantial reduction in radiation exposure to the patient using this technique. The thin-slice data set is sent to the 3-D workstation while the reformatted axial images are sent to the picture archive and communication system (PACS).

The exception to automated processing is the acute stroke patient who is a candidate for thrombolysis intervention. This scenario makes evaluation of the ICA, the basilar artery, the proximal MCA, the anterior cerebral artery (ACA), and the posterior cerebral artery (PCA) immediately at the scanner imperative. This is easy to accomplish by reviewing the data dynamically. If these vessels are not opacified while the other head vessels are and the symptomatic patient is in the therapeutic time window, then immediate intervention is indicated. CT perfusion scans can add value; however, their processing time at this point precludes their routine clinical use.

The CTA data set is best evaluated at the workstation. This workstation may be from a third-party vendor or the scanner vendor. The data set is initially selected, and then a rendering technique selected. Each major vessel may be isolated for review using trimming of the data, isolation of the vessel by selecting an area of interest, or use of a curved multiplanar reconstruction (MPR) technique. In neck CTA, each carotid artery is traced entirely for completeness, with emphasis on the carotid bifurcation. Usually, this is done using both volume-rendered and maximal intensity projection (MIP) methods. For vessels that have little calcification, the 3-D views work best. However, with calcification, the reformatted MIP projections are more accurate. Vertebral arteries are also evaluated from their origins to the basilar artery. Attention to vertebral origins with MIP projections identifies well any areas of stenosis. The raw data set is also evaluated for incidental findings.

For brain CTA, often a different rendering setting is used that optimizes smaller vessel assessment. Again, systematic evaluation of the vessels is needed, as well as an overview of the images for ancillary findings. This may be done by averaging slices and adjusting window and level settings to see brain parenchyma or bone detail. In the case of the circle of Willis, the vital viewing regions include the vertebrobasilar area, the basilar tip, the PCAs, the ACA, the MCA, and their proximal trifurcation vessels; the supraclinoid and cavernous ICAs; and the pericallosal arteries. The 3-D surface-shaded volume-rendered views see these areas best. Reformatted MIP views provide additional and complementary information in the case of vessel calcification, vasculopathy, and aneurysms. Reformatted and source images are used primarily at the skull nase where the clinoids and adjacent bones obscure volume-rendered 3-D views. CTV coverage is of the entire head. Review of the axial data set is supplemented by reformatted MIP images. The 3-D-rendered images are less helpful. In all cases, selected images of important findings are captured and saved. These are then sent to be added to the PACS data set.

CTA of the Neck

Carotid Vascular Disease

Several multicenter trials have established the need to differentiate medical versus surgical therapy on the basis of degree of carotid stenosis. The North America Symptomatic Carotid Artery Trial (NASCET) established that carotid endarterectomy provides an improved outcome over medical therapy in cases where the stenosis measures greater than 70% [4]. Measurement is by diameter of the maximal stenosis divided by diameter of the more distal internal carotid artery beyond any poststenotic dilatation. At 2 years, the stroke risk was reduced from 26% to 9% in the surgical arm while major stroke risk was reduced from 13% to 2.5%. In the 50–69% stenosis group, a modest improvement in outcome was present at 5 years with surgery. Surgical skill was an important determinant in outcome, and the results were better in men than in women [5]. The European Carotid Surgery Trial (ECST) found significant improvement in the surgical endarterectomy group, reducing stroke from 21.9% to 12.3% in stenosis of 70–90% [6]. This trial measured stenosis as the diameter of the stenosis divided by the diameter of the expected vessel wall.

In the asymptomatic patient, there are a few large studies worthy of mention. The Carotid Artery Stenosis with Asymptomatic Narrowing Operation Versus Aspirin (CASANOVA) study and

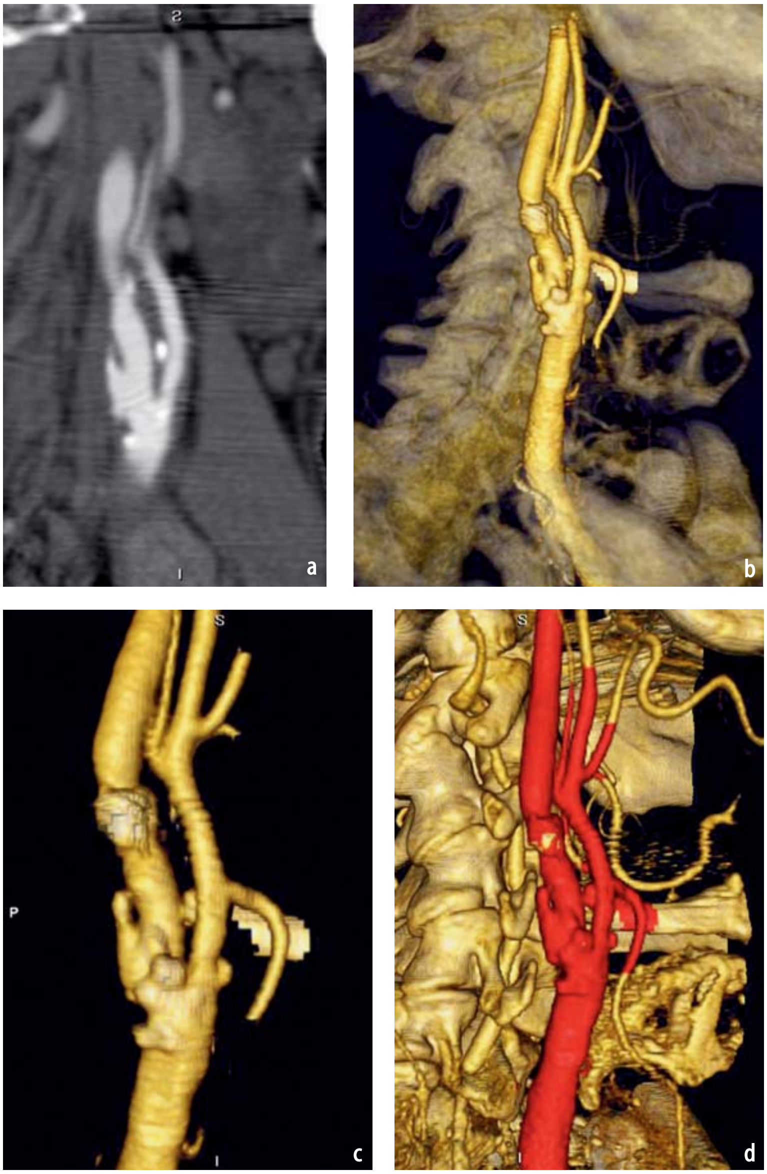


Fig. 2a-d. Carotid vascular disease on CTA. **a** Sagittal reformatted maximum intensity projection (MIP) demonstrates undermined, ulcerated plaque with moderate stenosis. **b** Volume-rendered surface-shaded three-dimensional (3-D) image of moderate stenosis and ulcerated plaque shows calcified plaque. **c** Magnified image with deleted background better exhibits carotid bifurcation region. The calcified plaque is lighter in this scheme, and the ulceration is well depicted posteriorly. **d** Automated vessel definition using a red color scheme example. Note the calcifications are not differentiated in this particular method

the Veterans Administration Asymptomatic Carotid Study (VAACS) are two of the earlier studies that have been overshadowed by the more recent Asymptomatic Carotid Atherosclerosis Study (ACAS) and Asymptomatic Carotid Surgery Trial (ACST) studies [7, 8]. The ACAS trial of 1,662 patients in 39 centers studied patients with greater than 60% stenosis. The 5-year stroke risk was 10.6% in the medical group versus 4.8% in the surgical group, resulting in an effective risk reduction of 1% per year with surgery. The benefit in women was much less with, relative risk reduction of 16% versus 69% in men [9]. The risk of surgery was less than 3%, and angiography constituted 1.2% of the total stroke risk. This often-cited statistic has helped to dramatically reduce the use of diagnostic angiography. The ACST study [10] involving 126 hospital trials in 30 countries followed 3,120 patients with greater than 70% stenosis. It demonstrated a 5-year stroke risk of 11.7% with medical therapy versus 6.4% with surgery. While there is criticism of the methods used in all of these trials, they all have clearly established the need for carotid artery evaluation.

Consequently, the most common indication for CTA of the neck is to assess vascular disease, most commonly carotid stenosis (Figs. 2–4). Its role in noninvasive testing is that of a secondary test along with magnetic resonance angiography (MRA). Ultrasound is a common noninvasive screening test for carotid assessment, and over two thirds of carotid cases are evaluated this way. If this test suggests only mild stenosis, then additional testing is not necessary. However, a moderate or severe degree of stenosis is worthy of further action. In many regions, ultrasound screening alone

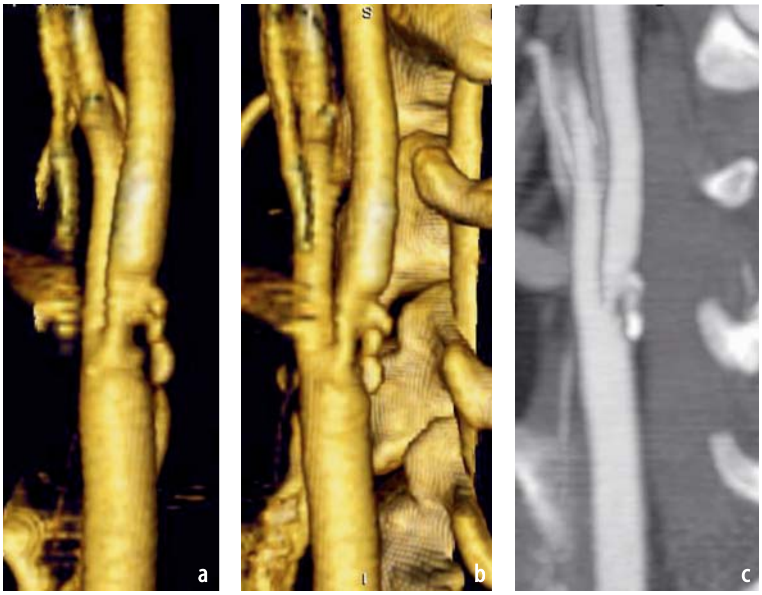


Fig. 3. Carotid vascular disease on CTA. **a** Coronal three-dimensional (3-D) image with eccentric plaque and approximately 70% stenosis. **b** Sagittal 3-D image with minimal calcification posteriorly. **c** Sagittal maximum intensity projection (MIP) reformatted image permits accurate viewing of severe stenosis and minimal calcification. Slice thickness and window/level settings affect visualized narrowing

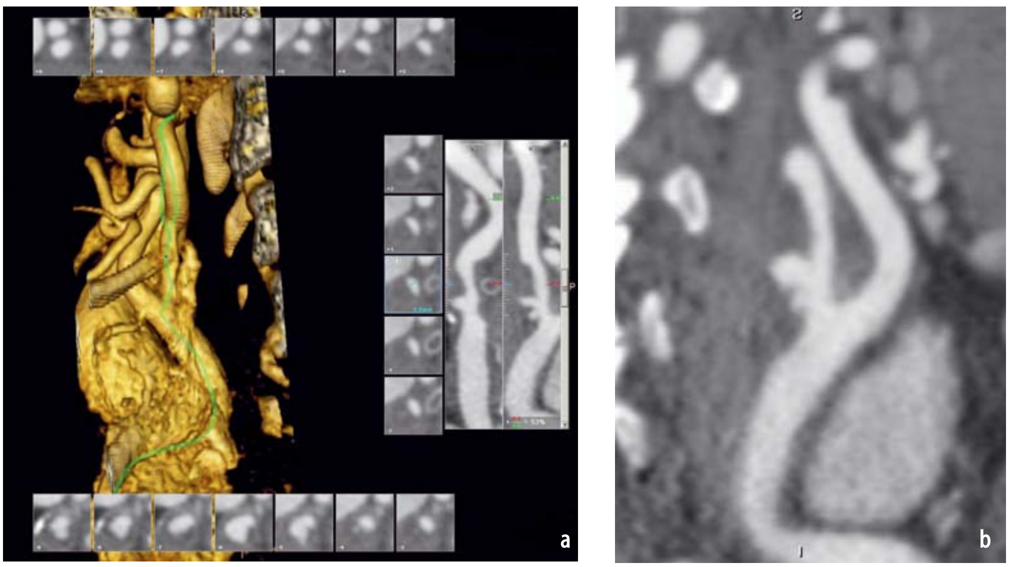


Fig. 4a, b. Carotid vascular disease on CTA. **a** Automated, curved, multiplanar reformation of carotid bifurcation. Multiple images are displayed perpendicular to the vessel long axis. Curved reformatted images to the *right* depict multiple ulcerations. The axial diameters are readily measured. **b** Manually trimmed sagittal maximum intensity projection (MIP) reformation also shows the multiple ulcerations with 50–55% stenosis

is seen as a clear surgical indication. However, the method does tend to exaggerate the degree of stenosis, so in cases of moderate or severe velocities, a correlative test may significantly improve accuracy and minimize false positives, thereby preventing unnecessary interventions. Also, this exam only evaluates a small window around the carotid bifurcation, not the entire vessel. The study by Johnston and Goldstein found a severe stenosis surgery misclassification rate of 28% on ultrasound results alone compared with conventional angiography [11]. While duplex ultrasound alone had a misclassification rate of 18%, the study illustrates the value of improved accuracy with multiple tests, reducing the miss rate to 7.9% with concordant exams. Consequently, if ultrasound is used as the screening modality, then MRA or CTA have value to confirm findings and provide additional information useful in patient assessment. This study has been confirmed by others.

MRA is also used widely for carotid evaluation. Most times, MRA is coupled with MR imaging (MRI) of the brain to evaluate the brain for stroke or other conditions and the vessels as a cause of the dysfunction. This “one-stop-shopping” method provides a useful clinical diagnostic procedure that is favored by neurologists. MRA can be obtained using time-of-flight (TOF) methods or with gadolinium enhancement [contrast-enhanced MRA (CEMRA)]. Improvements in MRI scanner gradient coils and slew rates have permitted more rapid data acquisition. Imaging methods such as elliptic-centric data ordering using 3-D fast-gradient-echo sequences or their equivalent allows the more important components of data to be captured when the contrast bolus is highest and for the scan time to be dramatically decreased. MRA is highly accurate. CEMRA tends to mildly overestimate degree of stenosis in the patient with severe stenosis. The two-dimensional (2-D) TOF method overestimates severe stenosis and may result in a "flow gap" due to intravoxel dephasing due to turbulent flow. Calcium is not evaluated since it does not have free hydrogen protons to give signal. The position of the carotid bifurcation is also difficult to assess. In cases of very severe stenosis, slow flow within a patent carotid may not be detected due to saturation effects inherent with MRA methods.

CTA of the neck provides many advantages and a few disadvantages compared with MRA and ultrasound. The entire vessel is evaluated, and the level of the bifurcation is clearly noted relative to the mandible. There is a small risk of allergic reaction due to iodinated contrast media. Radiation risk is difficult to quantify as to its significance but is of lesser importance in the typical older patient. Claustrophobia is certainly less of an issue than in MRI. The detection of calcification is a mixed advantage. This is an important feature to the surgeon and the interventionalist; however, it makes accurate stenosis analysis more difficult. While 3-D surface-shaded volume-rendered images are readily evaluated, in the case of calcification, the MIP reformatted images become the primary image of interpretation. In severe cases, the calcification must be windowed such that the calcium does not visually bloom and yet the vessel is well seen. Correlating the degree of stenosis in multiple planes improves the confidence level for an accurate reading.

Several papers have compared the accuracy of CTA, MRA, ultrasound, and conventional angiography [12, 13]. However, as the technology for each modality improves, the criteria by which they are judged is limited. One of the principal papers was written by Patel and colleagues in 2002 [12]. The sensitivity and specificity of ultrasound were 85% and 71%, of MRA 100% and 57%, and of CTA 65% and 100%, respectively. While the trend of MRA to overestimate and of CTA to underestimating stenosis but be more specific seems to hold, currently, MRA and CTA are considered to both be highly accurate with specificity and sensitivity in the 90–95% range. In our institution, neurologists favor MRA while vascular surgeons and interventionalists prefer CTA.

Stenosis alone does not fully predict who will present with neurologic events. The character of the carotid plaque is also important. Soft plaque and calcification are well depicted by CTA. Thrombus typically projects as a smooth intraluminal low-density image extending from an area of plaque. The detection of vulnerable plaque is more challenging to identify. The lipid-laden macrophages that are characteristic of vulnerable plaque are less focally defined than they are in the coronary circulation. Stratification of plaque by density is a potential way to suggest vulnerable plaque. Plaque with density below 60 HU is considered to be soft plaque that may be vulnerable while fibrous plaque may extend up to 150 HU. Ulceration is another plaque morphology that is hard to define, even by conventional angiography or direct inspection. A plaque that is undermined with a shelf-like appearance is suggestive of ulceration, but this is not definitive.

Carotid Occlusion

The diagnosis of carotid occlusion is clearly a forte of CTA (Fig. 5). The importance of this distinction lies in the potential for revascularization of a very severe stenosis, or "string sign" and the contraindication of surgery for occlusion. In actuality, it is important to distinguish between a small vessel with a focal severe narrowing that would be amenable to surgery and a diffusely irregular severely narrowed vessel that would preclude surgery. CTA is more of a volume technique than MRA, which is more flow sensitive. Consequently, CTA can provide this important information. With CTA, one can trace the lumen of the carotid artery and see if any contrast is visualized within it. If not, the diagnosis of occlusion is straightforward. Occlusion is also readily seen in the horizontal segment of the ICA. A pitfall is if imaging takes place too soon since slow flow may not be seen in this situation. Also of note is that collaterals from the external carotid artery can reconstitute the distal ICA, including the ophthalmic artery from ethmoidal internal maxillary artery branches, the artery of the foramen rotundum, and the Vidian artery.

Fibromuscular Disease

In addition to vascular stenosis, there are several other disorders that affect the carotid or vertebral arteries in the neck, including many of the collagen vascular disorders. One of these is fibromuscular dysplasia (FMD). This common disorder involves

Fig. 5a-c. Carotid occlusion. **a** Sagittal reformatted maximum intensity projection (MIP) demonstrates carotid occlusion. **b** The occluded right internal carotid artery can be well seen on the axial image of the neck (*arrow*). No contrast is present within the lumen. **c** At the skull base, the right carotid occlusion is diagnosed by lack of contrast within the lumen

the mid- and distal cervical ICA and the distal vertebral artery. Involvement of the neck vessels is present in 30% of cases; there is a strong female predilection. Irregular beading with small outpouchings and multiple small septations is the characteristic appearance. Areas of more focal dilatations or smooth stenosis are also variants that may be seen. Dissection and pseudoaneurysms are common, and FMD should be considered when these entities present. Intracranial aneurysms are also associated with FMD.

CTA of FMD can be difficult to diagnose (Fig. 6). This is due to the relative smoothing that is inherent to the CTA method. Careful assessment of the mid- and distal ICA and the V3 and V4 vertebral artery segments can demonstrate small irregular undulations or a more irregular enlargement.

Dissection and Pseudoaneurysm

The diagnosis of dissection should be considered in any younger patient who presents with headache or acute neck pain in association with a neurologic complaint. Minimal trauma may be associated. Horner's syndrome of miotic pupil, ptosis, and anhydrosis are frequently seen. The intimal disruption of the vessel results in an expanded vessel and compromised, smoothly narrowed lumen.

Both CTA and MRA are useful in the diagnosis and treatment of dissection (Fig. 7). The expanded vessel can be seen compared with the contralateral vessel, and the intimal flap is typically depicted. If there is flow on both sides of the flap, this is well seen, particularly on the source images. If one lumen is occluded, then thrombus may be evident with flow in the other compromised lumen. By MRA, fat saturation T1 sequences may show methemoglobin in the vessel wall. CTA depicts well vessel expansion and compromised lumen of the vessel. The characteristic involvement of the distal cervical ICA is well seen.

Pseudoaneurysms are often associated with dissections. These represent the focal vessel wall expansion with flow. CTA and MRA are both useful, but CTA demonstrates the location relative to the skull base and the exact dimensions.

The diagnosis of dissection and pseudoaneurysm is readily made by CTA and MRA. These are treated by anticoagulation or antiplatelet therapy in most cases. Consequently, having a noninvasive test to follow therapy is also helpful. Both CTA and MRA can be used for this purpose.

Vertebral Artery Evaluation

The vertebral arteries are well seen by CTA (Fig. 8). However, the adjacent vertebral bodies may overlay the vessel, particularly on the 3-D images. The

Fig. 6a-c. Fibromuscular dysplasia (FMD). **a** Irregular mid- and distal internal carotid artery (ICA) indicating FMD. **b** Maximum intensity projection (MIP) demonstrates the irregular vessel contour. **c** MIP on a different patient with FMD who also has pseudoaneurysm. Note the enlarged, tortuous vessel

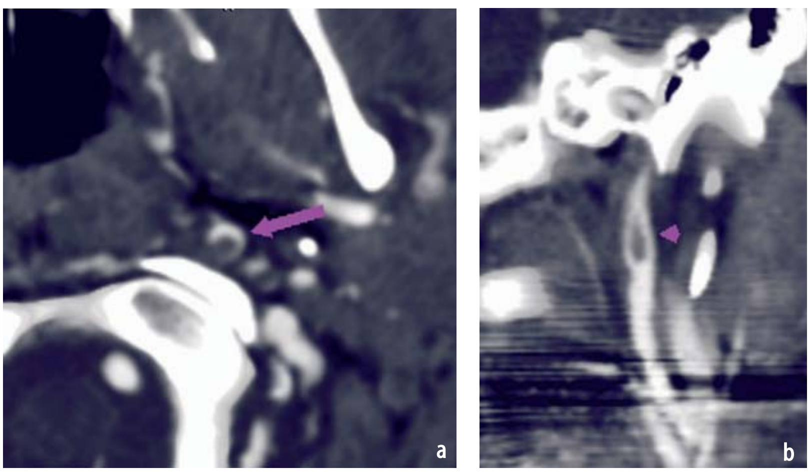


Fig. 7a, b. Carotid dissection. **a** Dissection of the left internal carotid artery (ICA) is diagnosed by enlarged vessel and compromised vessel lumen. Sometimes, a dissection flap is evident. Here, contrast is seen in the false lumen (*arrow*). **b** Reformatted image of dissection in a woman who was thrown from a horse. Note the dissection flap (*arrow*)

Fig. 8. Vertebral artery occlusion. Origins of the vertebral arteries can usually be well seen using thicker-slab maximum intensity projection (MIP) coronal images. Here, the left vertebral origin is occluded, and the ascending cervical artery reconstitutes the left vertebral artery in the transverse foramen at the C4 level. The right vertebral artery is hypoplastic

reformatted MIP images are useful to identify the vessel along with acquisition data. Normal variations of a dominant left vertebral artery or a vertebral artery ending in the posterior inferior cerebellar artery (PICA) are common. The origins of the vertebral arteries may be obscured by streak artifacts, superimposed contrast from the venous bolus, or calcification related to atherosclerotic disease. By magnifying the area of interest and adjusting the window/level of the image and adjusting the MIP slice thickness, one can usually resolve the vertebral artery well. In the case of atherosclerosis, measuring the maximal stenosis divided by the size of the normal vessel is used. Tortuosity of the vessel is often visualized in the mid-cervical spine region. Dissection of the vessel is more common distally.

Trauma

CTA has become the new standard in evaluating the patient with significant trauma to the neck or head [14]. The thin-slice CT technique provides evaluation of vessels in addition to surrounding soft tissue injury and evidence of fracture. Reformatted images also permit assessment of the cervical spine. Sensitivity for blunt cerebrovascular injury is quoted as 100%, with 94% specificity in a recent study by Berne [14]. Vertebral artery injury was more frequent than carotid injury, and there was a 21% mortality rate with vessel injury. Carotid canal fracture or transverse foramen fracture should alert one to the possibility of major vessel injury, specifically vessel dissection or occlusion (Fig. 9).

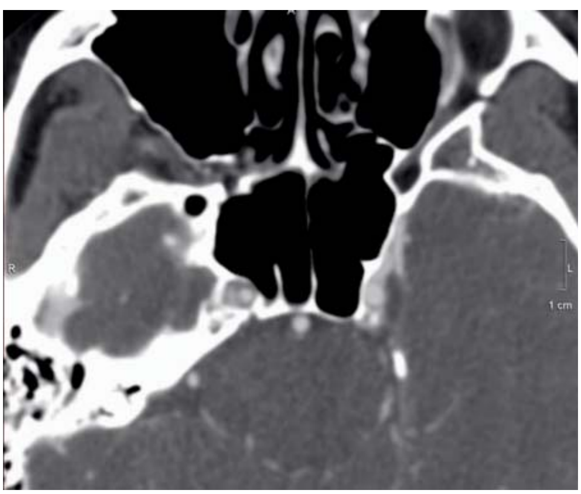


Fig. 9. Carotid traumatic dissection. CTA is used extensively to evaluate patients with significant trauma. Here, the right distal petrous internal carotid artery (ICA) is dissected in a patient post motor-vehicle collision. The compromised lumen is seen medial to the dissection laterally

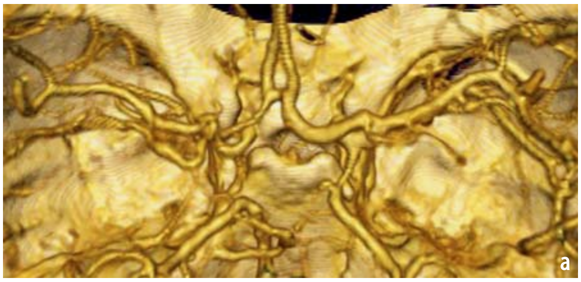
CTA of the Brain

In the past, the evaluation of intracranial vasculature required conventional angiography. However, the development of MRA and CTA provides a noninvasive method of assessing these vessels. A major challenge is the small vessel size. The horizontal segment of the MCA (M1 branch) and the basilar artery are typically 3 mm and the distal ICA is about 4 mm. The more distal branches get progressively smaller. Consequently, voxel resolution is an issue. Small fields of view and thin slices combined with slow table speed and low pitch provide the ability to see most major vessels. Systematic evaluation of intracranial CTA minimizes omissions. While there are many ways to do this, one easy and quick way is outlined as follows:

- Trim the data set to see the back of the foramen magnum and above the top of the basilar artery. Also, trim from the sides to see the MCA branches, excluding most of the calvarium.
- Look at the 3-D view posteriorly to view the vertebral arteries and proximal basilar artery. Rotate along the basilar to see the basilar tip.
- Look from the top of the data set to see the circle of Willis, following the vessels with slight rotations. This will view the posterior and anterior communicating arteries.
- Look from anteriorly to see the ophthalmic artery origins and distal ICAs. The anterior communicating artery and MCAs are also seen from this view with some additional rotation of data.
- Trim data to see just between the ICAs to evaluate the ACA territory branches. Then shift to the right and then to the left to see the MCA territory branches.
- View the coronal and sagittal reformats using MIP, and vary the slab thickness to see vessels of interest, particularly in the cavernous sinus region.
- View the entire data set to look for incidental and related findings, such as stroke, tumor, or AVMs. This may be done by averaging data to 5-mm thickness. Also look at venous drainage for thrombosis.
- Document findings of images of interest.

Stenosis and Occlusion

The major intracranial vessels are usually well seen by CTA [15]. Stenosis represents an area of narrowing in the vessel caliber (Figs. 10, 11). This is calculated as the diameter of the narrowing relative to the normal vessel caliber. Due to the small size of these vessels, it can be difficult to measure this exactly; however, magnification of the image helps to improve accuracy.



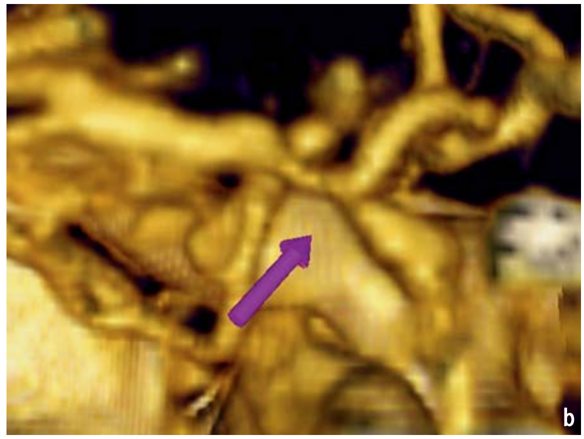


Fig. 10a, b. Intracranial stenosis. **a** Severe distal left internal carotid artery (ICA) and proximal middle cerebral artery (MCA) stenosis in this elderly patient with atherosclerotic disease causes reduced caliber of intracranial vessels. **b** By rotating and cropping the image, the severe stenosis at the ICA–MCA junction is well seen (*arrow*)

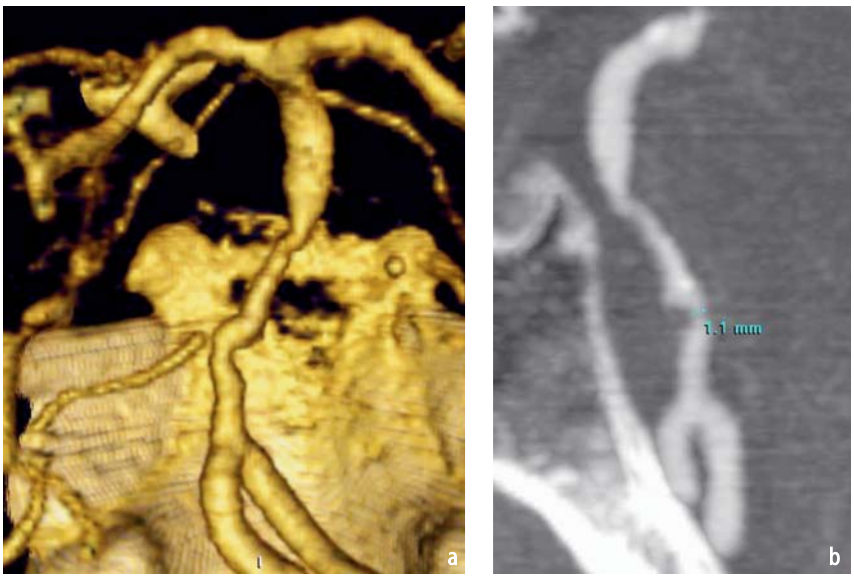
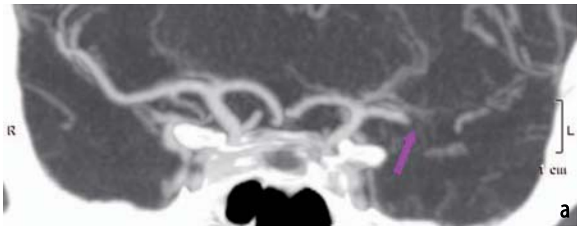


Fig. 11a, b. Intracranial stenosis. **a** Severe stenosis of the proximal and midbasilar artery due to atherosclerotic disease. **b** Sagittal maximum intensity projection (MIP) shows the irregularity of the basilar artery. Measurement of the vessel stenosis is demonstrated

Anomalies of the cerebral vasculature need to be considered as well. The left vertebral artery is equal or dominant in about 75% of patients, so asymmetry of the vertebral arteries is the rule. Frequently, a vertebral artery will diminish in size after the PICA origin. Also, hypoplastic P1 and A1 segments are frequently seen in about 25% of patients. These congenital narrowings should not be interpreted as acquired stenosis. The increased flow in the resultant compensatory feeding vessels makes aneurysms somewhat more likely, so these variations should be noted.

Stenosis of vessels is well seen on the 3-D images when the vessel is not calcified. However, in the setting of calcification, more reliance on MIP reformation is needed. The 3-D images will show a bump along the vessel wall, usually of a different color, but it can be complicated to differentiate the lumen from the calcified plaque. MIP reformation is more accurate to define the percentage stenosis. In addition, CTA is very useful in the case of anticipated endovascular intervention. Measuring the vessel size, stenosis diameter and length, and landing zones of a stent permit more accurate and, presumptively, safer angioplasty and stent placement.

Occlusion of a branch vessel may be straightforward to detect if one knows the cerebral anatomy to realize that a vessel is missing (Figs. 12, 13). Often, there is a small tail of contrast at the origin or an abrupt caliber change that defines the occlusion site. One pitfall of occlusion in major vessels is due to collateral flow. This reconstitutes the more distal vessel but at a smaller caliber due to reduced pressure and flow. The diagnosis of occlusion is made by tracing the pathway of the vessel and noting that no flow is present in a segment. To be sure of this finding, the image level should be increased using a narrow window to eliminate the possibility of a high-grade stenosis rather than an occlusion.



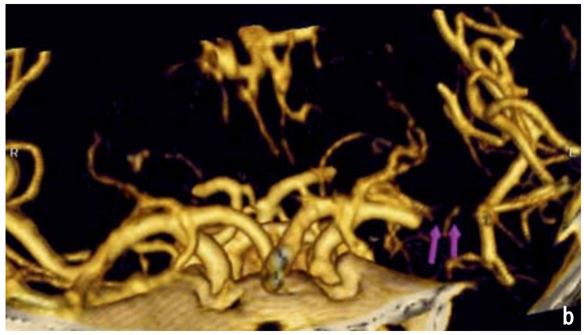


Fig. 12a, b. Acute thrombosis of the left middle cerebral artery (MCA). **a** Patient presents with acute right hemiplegia and aphasia. Thrombosis of the distal MCA is present, with occlusion of the distal M1 MCA segment and proximal M2 branches (*arrow*). **b** Three-dimensional (3-D) image of the acute thrombosis (*arrows*) demonstrates filling defect in contrasted vessels. Note reconstitution of distal collateral MCA branches

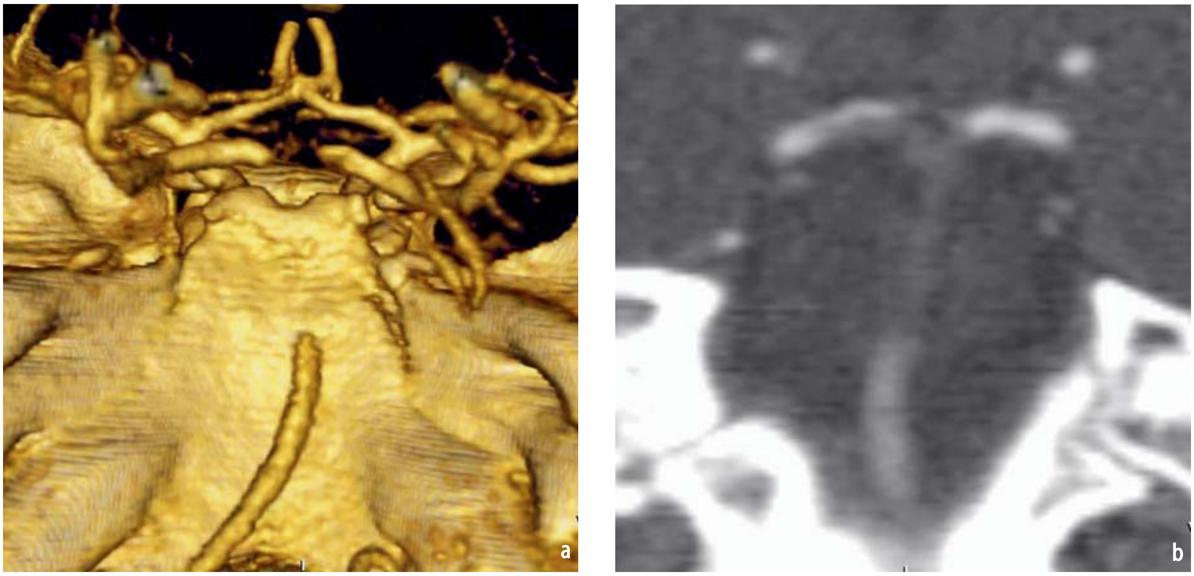


Fig. 13a, b. Acute basilar artery thrombosis. **a** Occlusion of the mid- and distal basilar artery is demonstrated in this patient who suddenly became comatose. **b** Coronal maximum intensity projection (MIP) image shows contrast opacification of the proximal basilar and posterior cerebral arteries with basilar artery thrombosis

Vasculopathy

Vasculopathy is a generalized term referring to any pathologic condition of the blood vessels. As such, it includes stenosis and occlusion and also includes vasospasm and vasculitis.

The detection of vasospasm by CTA has permitted a noninvasive method that complements transcranial Doppler [16]. Vasospasm typically arises in the 4–14 days following subarachnoid hemorrhage and is most common in the 7- to 10-day window. Standard clinical treatment includes "triple H" therapy consisting of hypertension, hypervolemia, and hemodilution in combination with the calcium channel blocker, nimodipine. This is effective in most patients, but in severe cases, endovascular angioplasty or arterial infusion is warranted. CT of the brain to evaluate for hydrocephalus and infarction is performed prior to intervention. In this situation, CTA can be added to the evaluation although in many cases the decision to proceed to conventional angiography has already been made, negating the value of CTA. The appearance of vasospasm on CTA is that of regions of smooth narrowing of vessels, including the major intracranial vessels.

Vasculitis is an inflammatory infiltration of the blood-vessel wall (Fig. 14). There are many etiologies that can be grouped by the size of the vessel involved. Takayasu's arteritis has large-vessel involvement of the great vessels up to the carotid bifurcation. It shows smooth vessel narrowing and a thickened vessel wall. Giant-cell or temporal arteritis may involve the larger cerebral vessels, including the classic superficial temporal artery. Most of these cases show areas of smooth narrow-

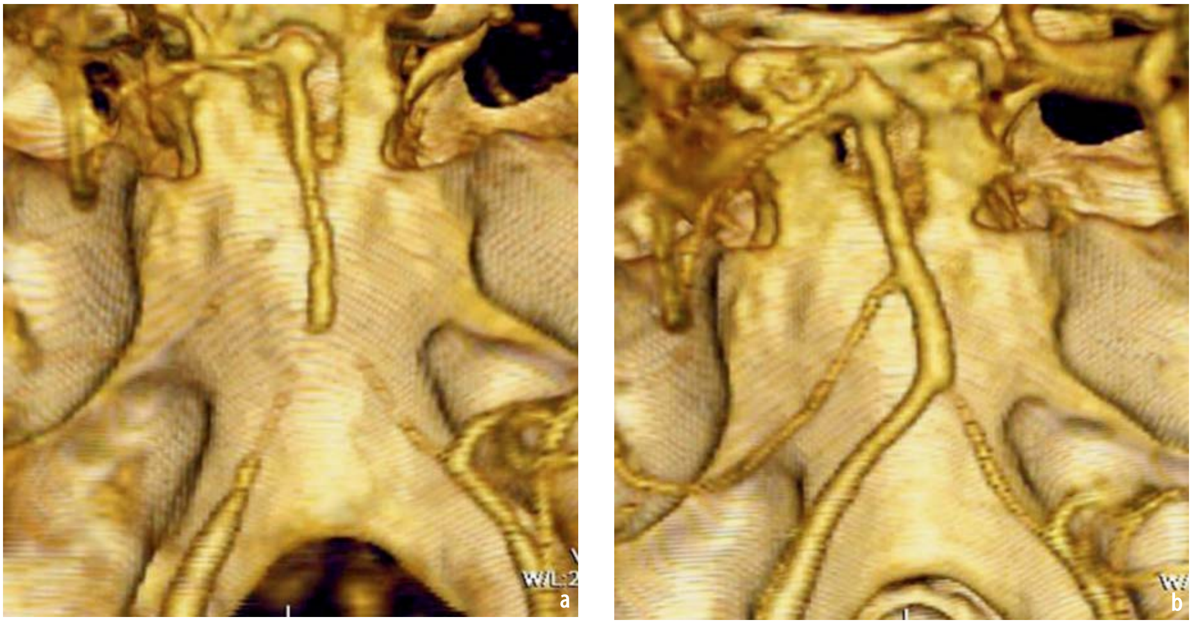


Fig. 14a, b. Vasculopathy. **a** Patient with sarcoid causing intracranial vasculopathy. Note narrowing of the basilar artery, distal vertebral arteries, and anterior inferior cerebellar artery. **b** Same patient after therapy demonstrates marked improvement in vessel caliber

ing of the vessel followed by a return to normal caliber – the so-called "beaded" appearance. There are also multiple autoimmune diseases and even primary CNS vasculitis with involvement of medium- to small-vessel beading. By CTA, involvement of the more proximal vessels is readily detected; however, medium- and small-vessel vasculitis is not able to be reliably found. Consequently, conventional angiography remains the standard diagnostic test.

Aneurysms

The detection of cerebral aneurysms by CTA has dramatically improved in the past few years. In many centers, it has moved to the forefront of evaluating patients with cerebral aneurysms [17–21]. There are two basic scenarios – the evaluation of the patient with subarachnoid hemorrhage (SAH) and the patient being screened or followed for cerebral aneurysm (Figs. 15–17).

SAH in the nontrauma patient without coagulopathy has a high likelihood of being due to a ruptured aneurysm. CT of the brain without contrast provides the diagnosis of SAH in most patients who present with the classical history of severe headache. Rarely, false negative cases may result from delayed presentation of the patient or from minimal amounts of blood in the spinal fluid. A compelling history warrants lumbar puncture (LP) for cerebral spinal fluid (CSF) analysis although the LP may also result in a traumatic tap. CTA provides a highly sensitive and specific method for detection and evaluation of cerebral aneurysms in all cases. A recent study by Karamessini and colleagues quotes a 93–100% sensitivity and 100% specificity for aneurysms 3 mm or larger. These values are comparable with conventional angiography [20]. In particular, anterior communicating artery aneurysms are seen equivalently or superiorly by CTA since both ACAs are visualized simultaneously.

MCA aneurysms, particularly complex aneurysms, are also seen equally as well or better by digital subtraction angiography (DSA). The basilar tip and artery and distal vertebral arteries are also evaluated equivalently or better by CTA. The posterior communicating artery is seen equivalently to DSA. Aneurysms that are seen better by DSA include those arising from the ICAs proximal to the ophthalmic arteries since adjacent bone can obscure the vessel on CTA. Also, mycotic aneurysms may be missed by CTA if they are not included in the imaging volume or involve small branches.

One advantage of CTA is that the aneurysm neck size and configuration can be accurately measured. Thus, the decision to surgically clip or endovascularly coil can be made in most situations. The need to reconstruct the parent vessel in the case of a broad-necked aneurysm is also suggested. CTA depicts calcified or partially thrombosed aneurysms. Calcification can be difficult to treat surgically. Thrombus within an aneurysm increases the risk of stroke or coil settling resulting

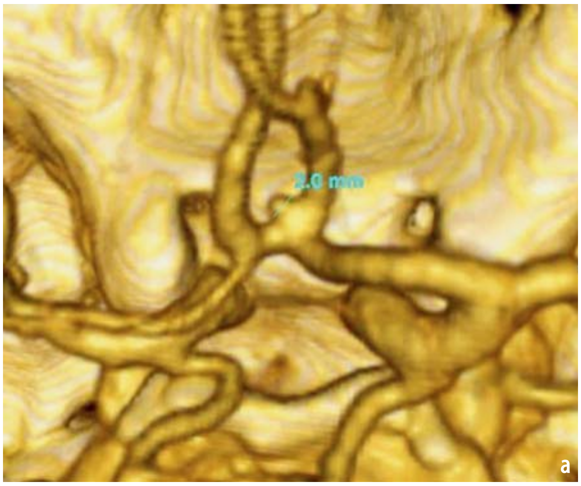


Fig. 15. Anterior communicating artery aneurysm. A small, 2-mm anterior communicating artery aneurysm is well visualized in this patient with prior subarachnoid hemorrhage (SAH) and "negative" cerebral angiography. By opacifying both anterior cerebral arteries simultaneously, the anterior communicating artery is typically seen better than by conventional angiography. Size and contours of the aneurysm are also well depicted

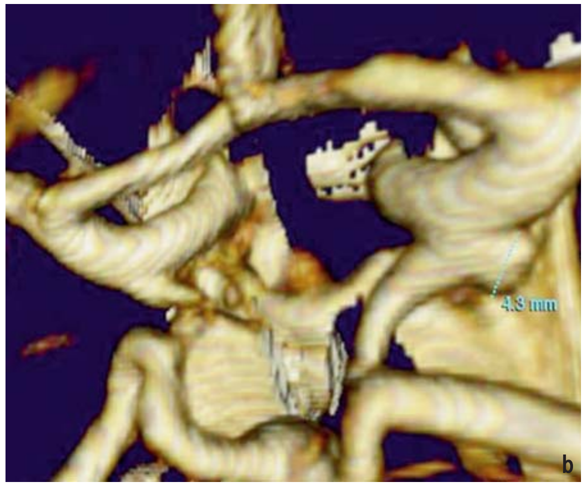


Fig. 16. Posterior communicating artery aneurysm. There is a 4-mm posterior communicating artery aneurysm in this patient who has a prominent associated posterior communicating artery. Note that the aneurysm neck is well seen, as is the contralateral infundibulum

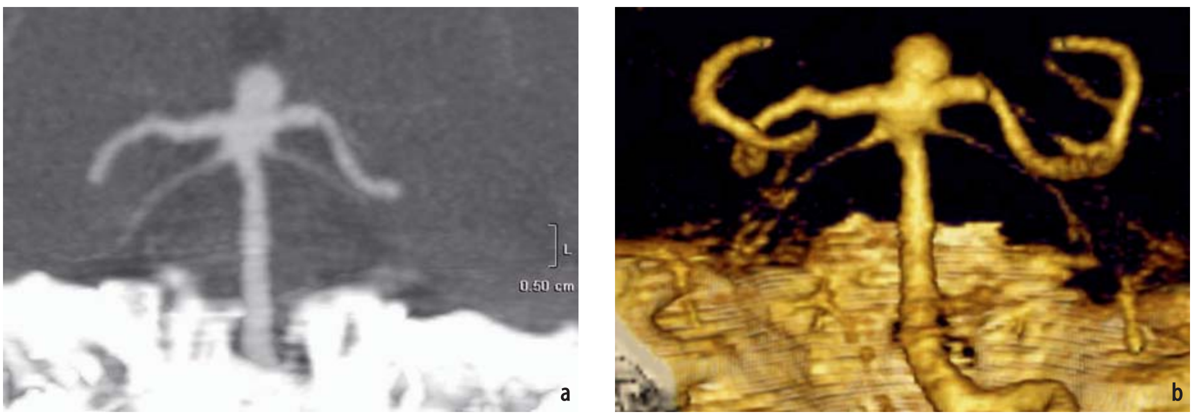


Fig. 17a, b. Basilar artery aneurysm. **a** Coronal maximum intensity projection (MIP) demonstrates the basilar tip aneurysm and relation to the posterior cerebral arteries with relatively broad neck configuration. **b** The three-dimensional (3-D) image gives better perspective of the aneurysm configuration

in incomplete treatment. Cases of endovascular stenting as an adjunct to coiling are also suggested.

An aneurysm may be detected incidentally in many cases where neuroimaging is performed. In the patient without SAH, finding an aneurysm presents a dilemma. Are the risks of rupture high enough to indicate treatment or should the aneurysm be followed medically? The International Study of Unruptured Intracranial Aneurysms (ISUIA) suggested that the risk of rupturing an aneurysm less than 10 mm is very low [22]. Many patients with incidental aneurysms are followed noninvasively to assess for interval change since a growing aneurysm is at higher risk for rupture. CTA provides an accurate means to measure and compare sequential exams.

Arteriovenous malformations (AVM)

The detection of AVMs is usually made by means other than CTA. In the case of ruptured AVM, brain CT without contrast demonstrates SAH, usually with parenchymal hematoma around the AVM. If the AVM is not ruptured, increased density or calcification at the AVM site is common and may be seen on noncontrasted CT. MRI shows flow voids, mixed signal intensity, and possibly hemo-

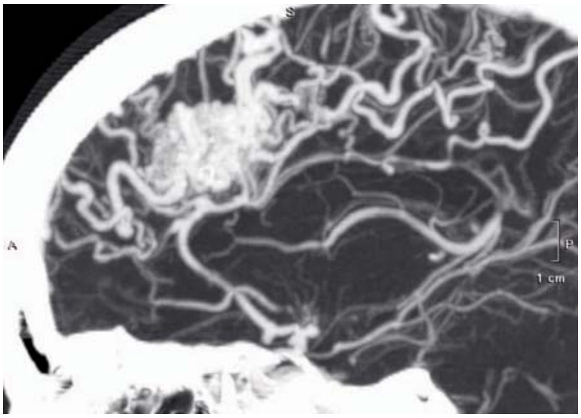


Fig. 18. Arteriovenous malformation (AVM). Sagittal maximum intensity projection (MIP) image demonstrates a 30cm AVM in the frontal lobe. Note the complex superficial venous drainage pattern. Aneurysms are also present in the distal internal carotid artery (ICA) posteriorly and the anterior communicating artery

siderin at the AVM. Conventional angiography is the procedure of choice for diagnosis since it demonstrates the relative flow in the feeding arteries, including dominant and lesser branches, and the nidus configuration. Most importantly, the venous drainage, including any venous constriction, is seen. CTA can be used to evaluate AVMs; however, the scan volume obviously needs to include the AVM and its feeding and draining vessels. The nidus is well depicted, which may be of benefit for radiosurgery planning. Associated flow-related aneurysms are well seen. However, it is difficult to see all the feeding arteries and to represent the relative flow in each branch (Fig. 18).

CT Venography of the Brain

CTV is a variation of CTA whereby the area of interest is the venous drainage rather than the arterial supply to the brain. As such, the timing reflects the transit time of blood to fill the venous system.

CTV Protocol

The entire head is included, using a 22-cm field of view with craniocaudal scanning using thin slices. For a 16-slice scanner, a pitch over 1 can be used with rotation time of 0.7 s. Tube load in the 320-mA range for 120 kVp with noise index of 5 provides excellent image quality. Image reconstruction at 2.5 mm or 1.25 mm is suggested. At the workstation, CTV is evaluated somewhat differently than CTA. The axial images provide the most information while reformatted data depicts the venous sinuses well. The 3-D images are sliced to look at the vertex and then the posterior head as an adjunct to the 2-D images.

Congenital Variants

The right transverse and sigmoid sinus are dominant in 50–75% of patients. Consequently, seeing a small left-venous sinus is common. Typically, the transverse sinus is smaller, and the sigmoid is a little larger due to inflow from the vein of Labbe and posterior fossa veins. The true size of the sigmoid sinus is easy to determine since the bony defect of the vein coincides with the vein on the CT source images.

The ability of CTV to show a hypoplastic sinus is one of its principal advantages over MR venography (MRV). Frequently, small low-density defects are visualized in the major venous sinuses. These represent arachnoid granulations where CSF is resorbed. MRV may mistakenly portray these defects as nonobstructive thrombus.

The significance of sinus stenosis is uncertain. If the sinuses connect, then compromise of one sinus is not of consequence. However, sometimes the sagittal sinus or straight sinus drains via only one transverse sinus. In these circumstances, severe sinus stenosis could be symptomatic [23]. Restriction of venous outflow inherently increases intracranial pressure, but the degree and nature of compensation is unknown. It has been postulated that there is an association with pseudotumor cerebri; however, the nature of this link and the contribution of other factors, such as the demographic association of an obese woman of childbearing age, is unknown.

Venous Thrombosis

Contrast-filled venous sinuses are commonly seen in almost every CTA and contrast-enhanced brain CT. By adjusting the window and level to see the contrast-filled veins, the entire venous system can be readily traced. Thrombosis represents a filling defect within the sinus and is readily evaluated [24] (Fig. 19). As a consequence of the venous obstruction, collateral veins along the sinus may be seen. As the thrombosis matures, the clot becomes adherent and synechia are seen. While thrombosis is demonstrated superiorly by CTV over MRV, MRI is better than CT at looking at the sequelae of the thrombosis. This includes venous infarction and cerebral edema. Hemorrhage, which is common with venous infarction, can be seen with both modalities.

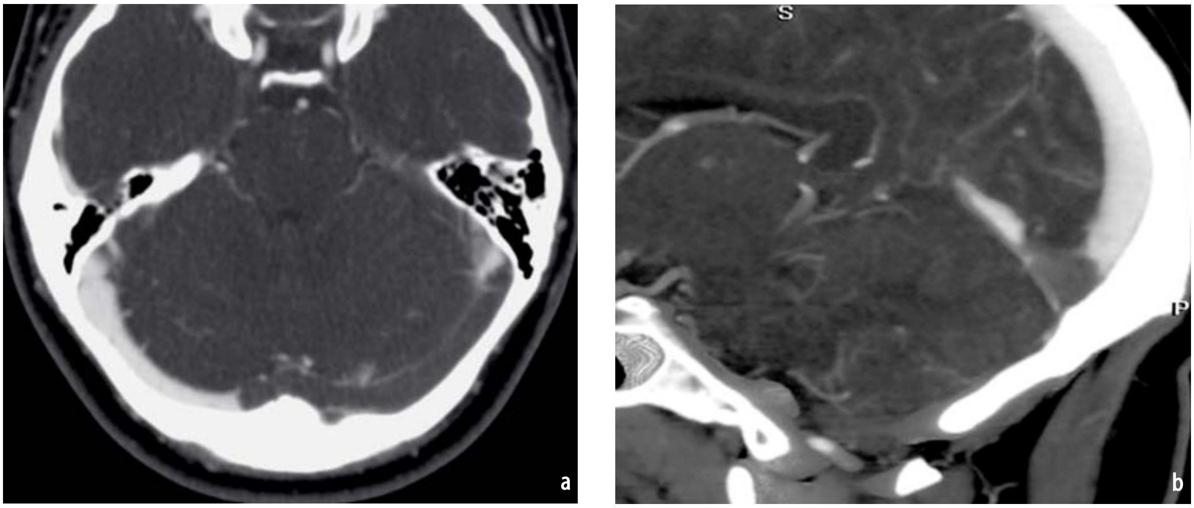


Fig. 19a, b. Venous thrombosis. **a** Axial image demonstrates a large filling defect of the left transverse sinus involving the torcula. This indicates acute thrombosis. **b** Sagittal maximum intensity projection (MIP) image demonstrates thrombus within the torcula. The posterior superior sagittal sinus and the straight sinus are widely patent and opacify with contrast

Summary

CTA provides an excellent method of evaluating the vasculature of the neck and brain. Technical improvements in MDCT and the improvement in workstation software provide for accurate diagnosis in a timely manner. In many cases, this currently replaces conventional angiography. The evaluation of carotid stenosis; trauma to the neck; and detection of cerebral stenosis, aneurysm, and thrombosis are but some of the growing indications for the routine utilization of CTA.

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