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# Neurovascular Applications of CTA: Stroke, Carotid Occlusive Disease, and Beyond

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## LEARNING OBJECTIVES

*Upon completion of this activity, participants should be able to:*

- Discuss the role of CT/CTA in the management of highly prevalent neurovascular diseases in general and stroke in particular.
- Apply basic technical principles of CTA acquisition.
- Explain how CTP may affect management decisions in acute stroke, including thrombolysis triage, blood pressure management, and ICU admission.
- Identify the role of postprocessing techniques to aid in CTA image interpretation.

Computed tomography scanning in the evaluation of the neurological patient has undergone a renaissance since the introduction of dual-head spiral scanning in 1992[1] and multislice scanning in 1998.[2] These advances have resulted in an increase in imaging speed and resolution that have made CT superior to MRI for certain applications, particularly in the field of neurovascular disease. Indeed, CT angiography (CTA) has largely replaced catheter arteriography for routine diagnostic assessments at many centers. This has had the greatest impact on stroke patients, for whom a timely and accurate diagnosis is

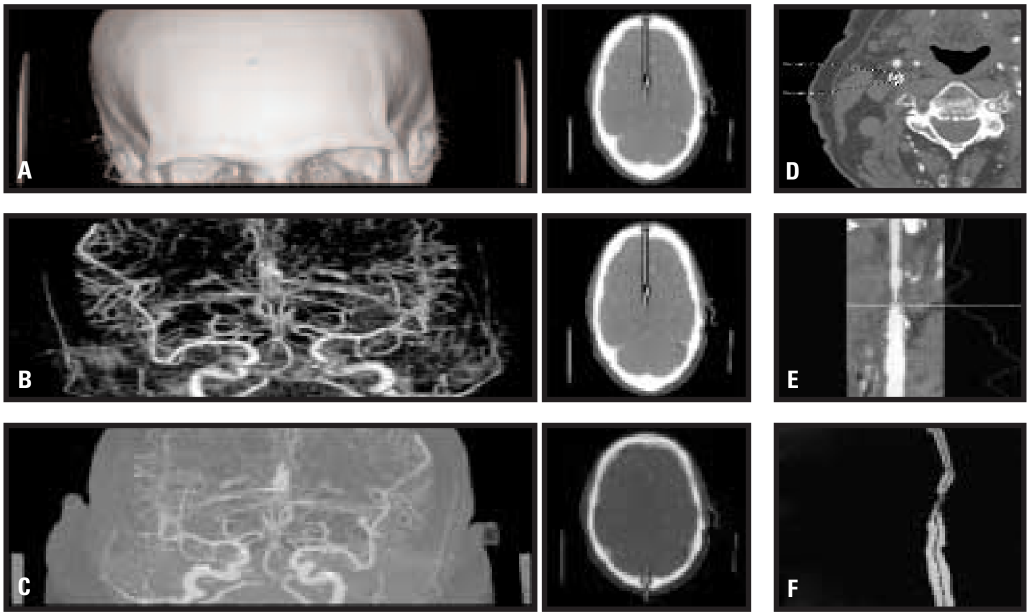

*FIGURE 1. Various applications of a neurovascular CTA data set. A: 3D volume (surface) rendering of skull. B: Volume-rendered projection of the major intracranial vessels following application of automated bone subtraction algorithm to data set. C: MIP resulting from application of automated bone subtraction algorithm to data set. D: Axial CTA source image following "seeding" of a right internal carotid artery endoluminal enhancing region, for creation of automated curved reformat through the entire length of the vessel. Note the automated computation of maximum and minimum cross-sectional diameter through the slice, as well as along the vessel's length. E: Automatic MIP curved reformatted image of the entire ICA, following application of the seeding region shown in 1D. Note again the automated computation of 3D cross-sectional diameter along the length of the vessel (histogram at right). F: MIP rendering of the automated curved reformatted vessel shown in D and E, using alternate display settings. (Provided by Mukta C. Joshi, GE Healthcare)*

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essential in their triage and treatment.

In addition, the emergence of CT perfusion (CTP) has added physiologic information to the management of these patients. With the greater availability of CT compared to MRI, especially in emergency departments, and the high prevalence of neurovascular disease, it is incumbent on neuroradiologists, even in community hospitals, to become acquainted with CTA.

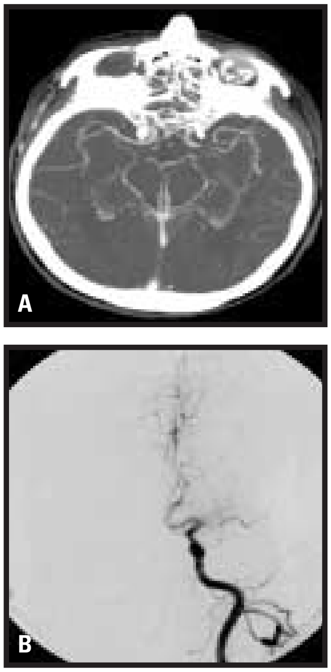

*FIGURE 2. A stroke CTA protocol. A: Axial MIP view of the circle of Willis demonstrates a proximal thrombus in the left M1 segment of the MCA. B: This finding is confirmed during digital subtraction angiography.*

### STROKE IMAGING

According to recent American Heart Association data, stroke is the third leading cause of death in the U.S, closely following heart disease and cancer. The only treatments of proven benefit are either IV thrombolytic therapy, using reverse tissue plasminogen activator (tPA) given within three hours of stroke onset, or intra-arterial (IA) thrombolysis, using tPA and/or mechanical clot retrieval, administered within six hours of stroke onset.[3-5] Newer thrombolytic agents, such as desmoteplase, have the potential to expand the time window for therapy to at least nine hours but are currently under investigation.[6] The role of imaging, advanced CTA in particular, is to address the following four questions:

- Is there hemorrhage?
- Is there a proximal large-vessel circle of Willis occlusion?
- Is there a "core" of tissue likely to be irreversibly infarcted, despite early recanalization?
- Is there a "penumbra" of hypoxic at-risk tissue that is potentially salvageable with early recanalization?

Asking these questions is essential for triage to both approved and investigational stroke treatments, and hence to inform a stroke imaging protocol.

•*Technique.* A multitude of potential imaging parameters can be manipulated in CTA acquisition. For a given level of image quality and total radiation dose, these parameters will vary according to scanner manufacturer, model, and generation (i.e., 4-, 8-, 16-, 64-slice MSCT).

Despite this variability, some important generalizations exist. For example, a unique consideration in scanning the brain, as opposed to other body parts, is the minimization of streak and "windmill" artifact through the posterior fossa. Typically, at least on older 4- and 8-slice scanners, posterior fossa imaging can be optimized by maximizing mAs, pitch, and gantry rotation speed and minimizing table feed.

Furthermore, acquisition protocols vary depending on the clinical question to be answered. Specifically, there can be minor differences in the rate and amount of contrast administered, as well as in table speed and pitch. For example, the stroke protocol is designed to obtain a "complete neurovascular workup" with CTA imaging from aortic arch to vertex and CTP imaging through the affected brain region. The aneurysm protocol, by contrast, covers only the skull base to vertex. Regardless of which protocol is used, however, patients should have a well-functioning intravenous catheter with a minimum diameter of 20 gauge (preferably 18 gauge) to handle injection rates >4 mL/sec.

To save time, the power injector should be loaded prior to patient arrival. The patient's head should be secured with tape or Velcro straps to minimize motion artifact. The gantry angle should be parallel to the orbital roof. Finally, instructions to patients should include not only "don't breathe," but also "don't swallow" during CTA acquisition. The carotid artery bifurcations are located at approximately the level of the larynx/hypopharynx and swallowing may result in severe motion artifact at just that portion of the internal carotid artery most likely to be critical in determining the need for carotid endarterectomy.

Nonionic, low-osmolar contrast is used because of the lack of neurotoxicity associated with nonionic contrast, as demonstrated in animal models of MCA infarction,[7,8] and the reduced nephrotoxicity associated with low-osmolar agents.[9] Also, low-osmolar contrast provides less of a volume load in patients at risk for congestive heart failure. With regard to a history of prior contrast reaction, gadolinium-enhanced CTA can be considered as an alternative to iodine-based contrast,[10] although milliliter for milliliter, gadolinium is more nephrotoxic than iodinated CT contrast and therefore cannot be used for CTA when there is high risk for contrast-induced nephropathy. Indeed, the most appropriate prophylaxis for CIN is adequate hydration and reduced contrast dose.[11] Although Mucomyst (acetylcysteine) has yielded mixed results in clinical trials testing its value in preventing CIN, recent studies have suggested that for high-risk patients (those with diabetes and/or baseline creatinine >1.9 mg/dL), bicarbonate is likely to be of benefit.[12]

In the triage of the acute stroke patient, the first task is to exclude intracranial hemorrhage. To this end, an unenhanced head CT is first performed. The head is scanned from the foramen magnum to the vertex and images are reconstructed at 5-mm intervals in "standard" and "bone" formats. Subsequently, contrast is administered for the CTA portion of the exam.

**TABLE 1. VARIABLES IN MDCT CTA IMAGING**

- **kV**
- **mAs**
- **Table feed**
- **Gantry rotation speed**
- **Pitch**
- **Slice collimation**
- **Reconstruction kernel**
- **Focal spot size**
- **Contrast injection rate/delay/ concentration/volume osmolality**
- **Saline push rate/delay/volume**
- **Postprocessing filters**

Our protocols call for the use of bolus tracking to determine the timing delay between the start of contrast administration and the start of image acquisition. With bolus tracking, when vascular opacification rises above a certain preset level (currently 30 Hounsfield units above baseline for our protocols), imaging is triggered. There is typically a minimum delay of at least three to four seconds between triggering and scanning. Bolus tracking facilitates optimal arterial opacification with minimal venous opacification, which is especially useful in assessing potential cavernous carotid artery aneurysms.

When single-slab CTP images are required, they are obtained following the CTA acquisition. Two 10-mm-thick or four 5-mm-thick CTP images can be reconstructed; thicker slices have improved signal-to-noise ratio. Unlike MR perfusion imaging, CTP imaging results in quantitative, high-resolution maps of cerebral blood volume (CBV), cerebral blood flow (CBF), and mean transit time (MTT), but are limited in their coverage to a total of approximately 2 cm per contrast bolus on most scanners.

Three-D-reconstructed maximum-intensity projection (MIP) images of the circle of Willis can be obtained from the source images (each slice 1.25 mm thick) directly at the CT scanner in less than a minute in the axial, sagittal, and coronal planes. A variety of commercially available software packages can be used to construct the CTP maps from the cine source data; the most accurate of these use deconvolution methodology, discussed at length elsewhere.[13,14] Like the MIP reconstructions, these can also be obtained directly at the scanner in minutes. More detailed reconstructions, such as curved reformats (CR) of the carotid and vertebral arteries, which are important diagnostically but not as urgent in acute stroke triage as the detection of intracranial occlusion, are analyzed offline at a networked freestanding workstation. Newer techniques,

**TABLE 2. 3D LAB PROJECTIONS USED FOR DEPICTION OF ANEURYSM CTA DATA SETS**

1. **"Collapsed" MIP (ACOM, MCA bifurcation, top of the ICAs, PCA)**
2. **Oblique axial MPR or MIP (MCA bifurcation)**
3. **"Handlebar" coronal MIP (anterior circulation)**
4. **Oblique coronal MIP (distal vertebral arteries, posterior inferior cerebellar artery origins)**
5. **Bilateral coronal and sagittal CR (ICAs)**
6. **Volume rendering of aneurysm for surgical approach**
7. **Coronal oblique MIP (ACOM)**
8. **Sagittal oblique MIP (PCOM)**
9. **Coronal oblique MPR (vertebrobasilar junction)**

**Anterior communicating artery = ACOM, middle cerebral artery = MCA, posterior cerebral arteries = PCA**

such as vessel seeding and bone subtraction, have the potential to significantly or fully automate the reconstruction process (Figure 1).

•*Image interpretation.* The CT/CTA/CTP stroke protocol is often reviewed at the scanner with the stroke neurologist, due to the urgent nature of the evaluation. In these cases, the patient is typically a candidate for thrombolytic therapy on clinical grounds; i.e., the time from symptom onset is less than three hours for the use of IV tPA, or six hours for IA thrombolysis or clot retrieval (note that longer but not as well-established time intervals apply to posterior circulation strokes). Image interpretation is tailored to determine whether the patient is an appropriate treatment candidate.

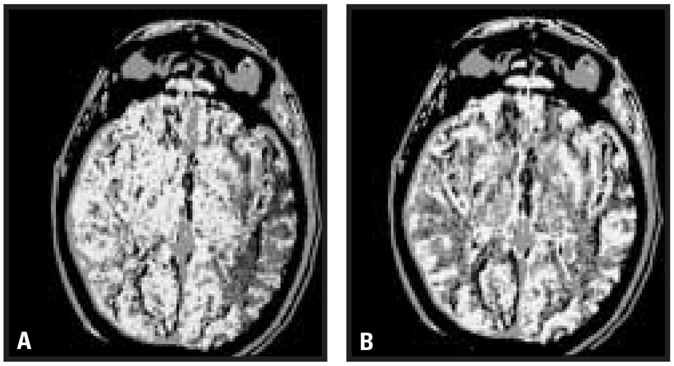

*FIGURE 3. CTP images from the same patient as in Figure 2. A: CBF map demonstrates a large area of decreased cerebral blood flow in the territory of the left MCA. B: CBV map demonstrates normal cerebral blood volume in the same region. The findings are consistent with a large territory of ischemic brain at risk for infarction. (Provided by Jennifer McGowan, 3D Imaging Lab, Massachusetts General Hospital)*

Specifically, the 5-mm-thick unenhanced head CT axial images are inspected for the presence of intracranial hemorrhage, which is an absolute contraindication to thrombolysis. In addition, the brain parenchyma is inspected to look for the loss of gray/white matter differentiation secondary to cytotoxic edema, indicating completed infarction. This is accomplished with narrow window width and center level review settings of approximately 30 and 30 HU, respectively, so as to increase the conspicuity of subtle attenuation decreases caused by increased tissue water relative to adjacent gray matter. Infarcted brain involving greater than one-third of a large vessel, e.g., MCA territory, constitutes a relative contraindication to thrombolysis.[15]

The 2.5-mm-thick, whole-brain, perfused images also provide a sensitive evaluation of infarcted brain. Indeed, the postcontrast CTA source images (CTA-SI)—assuming a steady-state level of arterial and tissue contrast during acquisition—have been shown to be CBV weighted.[16] In cases with early, complete recanalization, these images have been shown to correlate well with final infarct size in a manner analogous to that of MR diffusion-weighted imaging.[17]

CTA is highly accurate in the detection of proximal, large-vessel circle of Willis thrombus, and is therefore useful in the selection of candidates for IA thrombolysis.[18] The MIP views of the circle of Willis provide a more sensitive evaluation of the distal MCA branches (Figure 2).

CTP provides physiologic data that can be used to assess prognosis and predict clinical outcome. Quantitative maps of CBV and CBF, derived from the first-pass cine data set, can provide a profile of the ischemic penumbra, which is the area of hypoperfused but potentially salvageable brain (as determined by reduced CBF), and of the infarct core, ischemic tissue likely to be irreversibly damaged despite early successful reperfusion (as determined by reduced CBV) (Figure 3).[19,20] Patients with a significant CBF/CBV mismatch, i.e., those with much tissue at risk but small already-completed infarction and who are otherwise without contraindications, are typically the ideal thrombolysis candidates. Even outside the three to six-hour time window for thrombolysis, CTP may be useful to determine "brain at risk" in considering additional strategies for managing hyperoxia and blood pressure, and for intensive care unit monitoring. CTP can also provide criteria for entry into clinical trials of novel therapies, such as desmoteplase.[6]

Both CT and MRI can be used in the evaluation of the acute stroke patient. The most conspicuous advantage of MRI is its ability to provide a physiologic profile of the entire brain. Diffusion-weighted images accurately predict tissue destined to infarct, including even small lacunar and brainstem infarcts, and perfusion-weighted images display areas of "at risk" ischemic brain that may benefit from thrombolysis.[21,22] As noted above, CTP can provide data similar to that from MRP, but it is more limited in coverage. This advantage of MRI, however, is frequently outweighed by the more favorable speed, availability, and cost of CTA/CTP, which permits quick and accurate answers to the four critical imaging questions listed earlier. It is also clear that CTA is superior to MRA for rapid, accurate assessment of acute vascular occlusion and stenosis.[18] With regard to hemorrhage, MR susceptibility scans are likely more sensitive but less specific than unenhanced CT for the detection of acute parenchymal hematoma. But there is no evidence to date that this increased sensitivity, especially to chronic microbleeds, should alter patient management.[23] The entire CTA/CTP protocol adds approximately 10 minutes to the time of an unenhanced head CT.

## CAROTID OCCLUSIVE DISEASE AND DISSECTION

Severe extracranial carotid artery occlusive disease leads to an increased risk of transient ischemic attack (TIA) or stroke by serving as a source of emboli. In 1991, the North American Symptomatic Carotid Endarterectomy Trial (NASCET) demonstrated that patients with symptomatic internal carotid artery stenoses of at least 70% benefited from carotid endarterectomy.[24] As a result, imaging has taken on a vital role in the management of these patients by providing information about the degree of carotid stenosis. The excellent anatomic resolution of CTA makes it an important tool in the evaluation of carotid occlusive disease, as well as in the imaging of trauma when there is a question of carotid or vertebral dissection.

•*Image interpretation.* The postprocessed CT images provide an accurate screen for luminal stenosis. Precise measurement, however, is performed on the 1.25-mm-thick axial source images. We report the degree of vascular stenosis based on the residual lumen diameter. Critical stenosis is defined as a lumen diameter less than 1 mm. Severe stenosis is between 1 and 1.5 mm. Moderate-to-severe stenosis is between 1.5 and 2 mm. Moderate stenosis is between 2 and 2.5 mm.[25]

CTA measurements of residual luminal diameter are comparable to those of ultrasound, MR angiography, and conventional digital subtraction angiography.[15,26-28] In our institution, either ultrasound or MRA is used to screen patients for carotid occlusive disease. If there is a suspected stenosis, ultrasound and MRA are used together to confirm and estimate the degree of stenosis. If there is any question after this, CTA is used as a problem-solving tool. An advantage of CTA is that it excels at depicting anatomy, including the degree of atherosclerotic calcification, prior to surgery. It is also very accurate in distinguishing hairline residual lumen from complete occlusion.[26] However, an important pitfall to avoid is mistaking the ascending pharyngeal artery for a hairline extracranial internal carotid artery lumen.

*FIGURE 4. Posterior oblique volume-rendered reconstruction from an aneurysm protocol. CTA demonstrates two aneurysms (arrows) arising from the right ICA, in the paraclinoid region and at the ICA terminus. Note the relationship of the inferior paraclinoid aneurysm to the anterior clinoid process above it, which is important for surgical planning.*

In the setting of trauma, CTA has a high sensitivity and specificity for detecting major injury to the carotid or vertebral arteries.[29]

## ANEURYSM

Subarachnoid hemorrhage (SAH) from ruptured intracranial aneurysms is associated with a poor outcome: a mortality rate of 25% and significant morbidity in up to 50% of patients.[30] This poor prognosis is related to rerupture or vasospasm after initial rupture. Optimal management requires diagnosis and early treatment of the culprit aneurysm. To a lesser degree, this is true for arteriovenous malformations (AVM). CTA is an important tool for diagnosis and treatment planning.

•*Technique*. Compared to the stroke CTA/CTP protocol, our aneurysm protocol covers only the head. The field-of-view is decreased from the standard 22 cm to 20 cm or less in order to increase in-plane resolution. Slice thickness is 1.25 mm with 0.6-mm interslice spacing to improve 3D-reconstruction resolution. Imaging can be performed in the presence of surgical aneurysm clips by choosing the scanner gantry angle to minimize metallic beam hardening artifact.[31,32] Acute SAH evaluation requires CTA only; for vasospasm evaluation, CTP can be added.

The location of the aneurysm determines which projections optimally demonstrate its anatomy. We use standard projections that display the origins of every major intracranial vessel in at least two projections, which cover the most common sites of aneurysm formation.

•*Image interpretation*. The goal of image interpretation in the setting of SAH is to find the culprit aneurysm and define its anatomy. The location of the SAH helps to guide the search. For example, blood predominantly in one sylvian fissure suggests the presence of an ipsilateral MCA bifurcation aneurysm. This is especially useful when there are multiple aneurysms because it can favor one as the ruptured aneurysm that requires urgent treatment. Morphology also may help in deciding which aneurysm ruptured. All things being equal, the aneurysm with the more complex morphology, e.g., multiple daughter sacs, is the one most likely to have ruptured. When describing the aneurysm, it is important to describe the direction that it is pointing and to give measurements of the dome and the neck where it comes off the parent artery. These issues will help to determine whether the aneurysm is more suited for surgical clipping or endovascular coil embolization. The postprocessed image reconstructions, especially the VR projections, are useful for surgical planning (Figure 4). In our institution, CTA has replaced catheter angiography as the first-line imaging test for preoperative evaluation of patients with acutely ruptured aneurysms.

Ischemia related to vasospasm is the most significant cause of death and disability following aneurysm rupture.[30] Even after aneurysm treatment, the patient is at risk to develop vasospasm from the presence of subarachnoid blood. This typically occurs between days four and 14 after aneurysm rupture. Patients are monitored in the neurological ICU for changes in clinical exam and for increases in blood flow velocity in the major intracranial vessels as indicators of vasospasm. Blood flow velocity is determined via bedside transcranial Doppler interrogation. If there is concern for significant vasospasm, the patient is taken to catheter angiography for evaluation and possible treatment. We have begun to use CTA/CTP as an adjunctive tool in the evaluation of vasospasm. CTA has been shown to be highly accurate in the detection of proximal circle of Willis vasospasm.[33] CBF reduction, as determined by CTP, has been shown to correlate with clinically symptomatic vasospasm.[34,35]

In the nonacute setting, both CTA and MRA can be used for the screening of patients at high risk for aneurysm (e.g., those with positive family history or polycystic kidney disease), or for follow-up of those with incidentally found aneurysms. As with occlusive disease, CTA is often used as a "problem solver" when the results of MRA are unclear.

## OTHER APPLICATIONS

The CTA protocol can be modified to include a longer delay after contrast injection so as to evaluate for venous thrombosis. Quantitative CTP maps are beginning to be used to monitor brain tumor angiogenesis. Future applications may include evaluation of Alzheimer's dementia and traumatic brain injury.

## SUMMARY

Recent advances in CT technology have resulted in a rebirth of CT, especially in the field of neurovascular disease. The speed and resolution of CTA/CTP make it a powerful tool in the evaluation of acute stroke, carotid occlusive disease, traumatic carotid or vertebral dissection, and aneurysmal SAH. CTP adds important physiologic data that predict outcome and affect treatment decisions. Postprocessing techniques have become increasingly important in the interpretation of these complex data sets.

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