Introduction

The term **acute stroke** refers to a constellation of symptoms and clinical signs that indicate the presence of a sudden neurological injury secondary to vascular occlusion or injury. As many as 20 million people are afflicted by stroke annually worldwide, and the prevalence of stroke survivors is at least 60 million by some estimates.1 Stroke is a significant cause of mortality, resulting in more than 140,000 deaths annually in the US alone, and stroke survivors suffer long-term neurological impairment, decreased quality of life, and represent a significant burden to society in both expense of management and loss of productivity.2

The underlying causes of acute stroke are commonly grouped into three categories: ischemic, hemorrhagic, and venous. **Ischemic stroke**, arising from acute arterial occlusion and subsequent ischemic injury and infarct, accounts for approximately 80% of acute strokes and will be the primary focus of this review. The other 20% of acute strokes are classified as **hemorrhagic stroke**, which includes primary intracranial parenchymal and subarachnoid hemorrhages, and **venous stroke**, which is caused by occlusion of the intracranial venous sinuses and cortical veins and results in distinctive patterns of congestive injury and hemorrhage.3

Emergency imaging plays a key role in the management of acute stroke.4,5 The initial goal of imaging in acute stroke is to exclude the presence of intracranial hemorrhage prior to the initiation of intravenous tissue plasminogen activator (IV tPA) in eligible patients. After hemorrhage is excluded, the secondary goals are to identify the location of the arterial occlusion and to characterize the affected brain parenchyma as irreversibly damaged (infarct) or “at risk” for infarction (ischemic penumbra) when endovascular therapy is available. Finally, global assessment of the arteries of the head and neck is recommended in all patients following acute stroke5 to help identify the mechanism of the stroke and stratify future risk, and to identify the location of occlusion for possible endovascular revascularization, where available.

Commonly used imaging modalities for stroke include computed tomography (CT) and magnetic resonance (MR) techniques, including nonenhanced CT (NECT); abbreviated MR protocols using T2 fluid attenuated inversion recovery (FLAIR)-weighted sequences, T2*-weighted gradient-echo (GRE) and susceptibility-weighted (SWI) sequences, and diffusion weighted (DWI, DTI) and apparent diffusion coefficient (ADC) MR; CT angiography (CTA) and MR angiography (MRA); and CT or MR perfusion (pCT and pMR, respectively). Doppler ultrasound (DUS) is appropriate for evaluation of the vessels of the neck, although review of carotid ultrasound is beyond the scope of this article.

Nonenhanced Computed Tomography

Computed tomography is the initial imaging evaluation of choice in patients with clinically suspected acute stroke due to its wide availability, short exam duration, and high presumed negative predictive value for acute intracranial hemorrhage.
(ICH). The presence of acute intracranial hemorrhage is an absolute contraindication for administration of IV tPA and must be performed and interpreted rapidly in order to prevent delays in therapy for eligible patients. In addition, other possible etiologies of the patient’s neurological deficits (e.g. intracranial mass, hydrocephalus, etc.) may be suggested at the time of the initial NECT exam.

Initial scans are often grossly normal or nonspecific following acute ischemic stroke prior to the onset of parenchymal edema and swelling. The hyperdense (or dense) MCA sign (Fig. 1) and related dot sign (Fig. 2) are insensitive but specific early findings in M1 or M2 segment MCA ischemic strokes, representing high attenuation thrombus within the affected vessel. These signs are of particular importance, because they may be present from the very onset of the vascular insult prior to any additional NECT findings. Hyperdense thrombus may also be seen in less commonly involved vessels, including the intracranial ICAs, anterior cerebral arteries (ACAs), posterior cerebral arteries (PCAs), and basilar artery.

A later, but early sign of proximal M1 or proximal M2 occlusion is the insular ribbon sign (Fig. 3), representing loss of normal grey-white matter attenuation differentiation in the insula due to cytotoxic edema. Developing cytotoxic edema may also result in an indistinct or hypoattenuated appearance of the architecture of the basal ganglia relative to the contralateral side referred to as a “disappearing” basal ganglia sign (Fig. 4).

As the ischemia progresses to infarction and cytotoxic edema continues to develop, occlusions involving larger vascular territories will be evident as geographic regions of decreased attenuation in a vascular distribution with associated loss of normal grey-white matter differentiation (Fig. 5). Accurate description of the size of the region has prognostic significance. The Alberta Stroke Program Early CT Score (ASPECTS) criteria divides the subcortical and cortical brain into 10 standardized zones; MCA strokes scoring 7 or more affected zones are associated with higher risk for symptomatic hemorrhage and a poor functional outcome. Similarly, the “one-third” rule stipulates that if greater than 1/3 of the MCA territory is affected, there is a greater risk of symptomatic stroke.6,7
Some institutions use protocols in which MRI is used in initial evaluation of suspected acute stroke. Acute stroke MRI protocols are typically abbreviated relative to protocols for non-acute stroke and other disease entities, and are often limited to DWI/ADC, T2*, and T2 FLAIR sequences. There are several disadvantages of MRI relative to NECT. Even stroke-specific MRI scan times are longer than NECT exams and protocols must not overly delay (or prevent) tPA administration for eligible patients. MRI is more likely to be degraded by patient motion and may be nondiagnostic in patients who are unable to fully cooperate. Patients with metallic hardware in the head and/or neck and patients with implanted electronic devices (e.g. pumps, pacemakers, nerve simulators) are similarly poor candidates for MR based imaging. Benefits of MR protocols include decreased exposure to ionizing radiation, improved detection of posterior fossa stroke, better characterization of stroke mimics, and superior differentiation between acute and chronic ischemic changes.

In the initial evaluation for evidence of intracranial hemorrhage, T2* sensitive sequences (i.e. GRE and SWI) are highly sensitive, appearing as low signal “blooming” caused by local magnetic field inhomogeneity (Fig. 6). Despite high sensitivity for the presence of blood, residual hemosiderin from prior hemorrhage and benign intracranial calcifications are confounding (Fig. 7) and may be indistinguishable from acute blood products if comparison imaging is not available. Punctate regions of suspected “microhemorrhages” may be present and should be reported; these commonly represent sequelae of prior hypertensive or amyloid angiopathy and hemorrhage, and it has been suggested that a large number of these lesions may increase the risk of hemorrhage following thrombolysis.9,10,11

There is a high degree of concordance between MR and NECT findings in acute cerebral ischemic stroke, although MRI is more sensitive than NECT for detecting anterior circulation stroke in the first 24 hours after vessel occlusion.12 T2 FLAIR is more sensitive for early cerebral edema than conventional T2 sequences, demonstrating coarsening of the cortical sulci, increased parenchymal volume, and abnormal signal hyperintensity (Fig. 8A and B), and will be almost universally abnormal 6-7 hours following stroke onset, compared to 12-24 hours for T2.

DWI is superior to NECT in the detection of acute ischemia in the brain, with a sensitivity reported up to 99% by 24 hours.13,14 Ischemia results in rapid cytotoxic edema and decreased membrane permeability, leading to a decrease in ADC values and corresponding increase in DWI signal characteristic of restricted diffusion (Fig. 8C and D) which correspond with late acute appearance of NECT (Fig. 8E). DWI will detect smaller infarctions than NECT and is the

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**Figure 6.** “Blooming” on susceptibility-weighted MRI. GRE is highly sensitive for blood products. GRE image in a patient with subarachnoid hemorrhage (A) demonstrates “blooming” or susceptibility phenomenon, which increases conspicuity of SAH not clearly seen on CT. Axial CT (B) and GRE (C) in different patient shows increased conspicuity of blood products within the medial right cerebellar hemisphere on GRE compared to CT.

**Figure 7.** GRE hemorrhage mimics. Calcifications of the basal ganglia (A, circled), pineal gland (B, arrowhead), and falx (B, arrow) demonstrate susceptibility that may be difficult to definitively distinguish from hemorrhage at times. Calcified choroid plexus commonly demonstrates “blooming.”

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preferred modality for evaluation of patients presenting with TIA, potentially demonstrating small infarcts that would otherwise remain undiagnosed. The presence of restricted diffusion in patients presenting with TIA is associated with higher incidence of future ischemic events, and the distribution of findings may be used to identify the etiology of the ischemic injury. Specifically, lesions in multiple vascular distributions suggest thromboembolic disease; bilateral strokes are associated with cardioembolic disease; and “watershed” infarcts suggest proximal high-grade vascular stenosis (Fig. 9).

In posterior fossa ischemia, the large volume and proximity of high density compact bone in the skull base causes local beam hardening, which severely limits detection of subtle brain attenuation changes in the posterior fossa and brainstem with NECT. DWI is largely unaffected, and even small regions of restricted diffusion may be readily evident (Fig. 10).

MR and CT Angiography

Early angiography of the head and neck is increasingly a component of acute stroke imaging. CT angiography is more widely used; eligible patients may be administered IV tPA while still in the scanner following initial NECT imaging to exclude hemorrhage and immediately be rescanned with contrast for angiography of the head and neck with or without pCT, depending on the institutional protocol.

Although both CTA and MRA have similar accuracy
in identifying proximal anterior circulation occlusions,\textsuperscript{19} each modality has its limitations. Although more widely used, CT angiography is contraindicated in patients with a history of severe contrast reaction and is relatively contraindicated in patients with severe renal insufficiency, although contrast induced nephropathy (CIN) may be an acceptable risk in stroke patients. CT-based imaging is degraded by metallic artifact and posterior fossa beam hardening. MRI/MRA may expedited in patients with suspected posterior fossa stroke, as discussed above; however, MRA presents its own limitations. In addition to general MR considerations discussed above, risk of nephrogenic systemic fibrosis (NSF) limits the use of gadolinium-based contrast for contrast-enhanced MRA, although noncontrast time-of-flight techniques may still be applied. Time-of-flight noncontrast MRA, however, is subject to flow-related loss of signal which may simulate or overestimate stenosis in affected vessels.

In patients with intracranial hemorrhage, CTA of the head is routinely performed to evaluate for a causative lesion (e.g. aneurysm, tumor, vascular malfunction, etc.). In institutions where endovascular therapy is available, head and neck CTA allows for identification of the site of occlusion to guide possible endovascular therapy in patients ineligible for IV tPA (e.g. outside the 0-4.5 hour treatment window) or with large ICA and MCA occlusions\textsuperscript{20,21}, as discussed below.

MR and CT Perfusion Imaging

Both pCT and pMR are techniques available to further characterize a suspected region of ischemia. Both techniques attempt to delineate irreversibly damaged or infarcted parenchyma from potentially retrievable “at risk” non-infarcted brain tissue. The leading motivation for this distinction is two-fold: large regions of “at risk” brain outside the IV tPA window and proximal occlusions that are less likely to respond to IV tPA alone may be indications for endovascular therapy.

It is important to note the current state of the literature regarding the use of both endovascular revascularization therapy and the use of perfusion imaging in evaluating stroke. Some evidence exists for therapeutic benefit of intra-arterial tPA administered up to 6 hours post onset\textsuperscript{22,23} or mechanical thrombectomy even after the 0-4.5 hour IV tPA window has passed.\textsuperscript{24,25} Subsequent trials, however, have challenged the efficacy of these therapies,\textsuperscript{26-28} and additional trials are necessary to more accurately identify patients who may benefit from intrarterial thrombolysis and mechanical thrombectomy. In addition, although perfusion imaging is often performed prior to endovascular therapy as a component of patient selection, to date several trials have not demonstrated strong prognostic value of perfusion imaging in predicting IV or endovascular therapy outcomes.\textsuperscript{29-32} Institution-specific and clinical trial guidelines, however, are used to determine reperfusion eligibility based on the size of the infarct core, largely based on the known increased risk of hemorrhage in patients based on established NECT criteria.

Perfusion imaging is proposed as a potentially useful assessment of remaining viable ischemic tissue that may benefit from reperfusion, and the basis of perfusion imaging is the different imaging characteristics of ischemic and infarcted brain. Prolonged ischemia may progress to infarct, although the time from ischemia to infarction varies by patient. Quantitatively, cerebral ischemia is associated with

\begin{figure}[h]
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\caption{Penumbra on pCT. pCT performed at initial presentation 2 hours after onset of symptoms demonstrates decreased CBF (A) and increased MTT (B) in the left MCA territory without associated change in CBV (C). This appearance suggests a large region of ischemia not yet irreversibly infarcted.}
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CBF of less than 20-25 ml/100g/min,\textsuperscript{23,34} and values of 12-25 ml/100g/min are more likely to recover with return of normal perfusion.

In pCT, quantification of inflow of contrast material allows calculation of blood flow (cerebral blood flow, CBF, and mean transit time, MTT) and blood volume (cerebral blood volume, CBV). Brain parenchyma with decreased CBF, increased MTT, and normal CBV suggests ischemia without infarct, or a vascular penumbra of brain “at risk” of infarct. Decreased CBV is associated with greater degree of cerebral edema and cell death. The “mismatch” between decreased CBF and decreased CBV is believed to represent brain that may recover if perfusion is normalized (Figs. 11 and 12A-C).

Although less widely used, in pMR, the penumbra is determined by the mismatch between the region of decreased CBF (calculated during dynamic imaging during administration of gadolinium-based contrast) and the size of the core infarct determined by DWI. This is analogous in interpretation to CT-based perfusion techniques.

Figure 12. Penumbra progressing to infarct.

pCT performed at initial presentation 4 hours after the onset of symptoms demonstrates decreased CBF (A) and increased MTT (B) in the right MCA territory. Smaller central region of decreased CBV (C) suggests an “infarct core” with a surrounding penumbra not yet infarcted but “at risk.” CTA performed at time of pCT identifies the site of right distal M1/proximal M2 occlusion (D). Patient declined endovascular therapy. At 48 hours, DWI (E) and NECT (F) demonstrate evolution of infarction progressing from the infarct core identified in CBV to involve the entire region of ischemia initially indicated by decreased CBF.

Summary

Imaging of acute stroke is routine practice in emergency radiology. Although institutional variation exists, established evidence-driven guidelines direct the standard of care in order to enable timely and effective medical management. Both CT and MR based techniques are effective in the diagnosis and characterization of both ischemic and hemorrhagic stroke and vascular imaging of the head and neck is routinely performed at the time of initial presentation for prognostic purposes and to guide possible endovascular therapy, where available. Vascular and perfusion imaging may be incorporated into protocols to assess patient eligibility for endovascular therapy; however, additional study is needed to better establish value of both perfusion imaging and endovascular therapy.
References


