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Advancements in Radiology Imaging for Stroke Management

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Abstract

Neuroimaging has become an integral component in the diagnosis and management of acute ischemic stroke (AIS), with recent advancements leading to a paradigm shift towards tissue- and imaging-based approaches for treatment decisions. This review explores the commonly utilized imaging modalities, including computed tomography (CT), magnetic resonance imaging (MRI), and advanced perfusion imaging techniques. Noncontrast head CT remains the preferred initial imaging modality for suspected stroke, providing high sensitivity for detecting intracranial hemorrhage and early ischemic changes. CT angiography enables rapid evaluation of extra- and intracranial occlusive diseases, while CT perfusion assesses cerebral tissue perfusion, estimating the ischemic core and penumbra. MRI, particularly diffusion-weighted imaging, exhibits high sensitivity, specificity, and accuracy in detecting early ischemia. MR angiography and perfusion provide insights into vascular pathology and tissue viability. Ultrasonography offers real-time assessment of cerebral blood flow, while positron emission tomography and single-photon emission computed tomography visualize pathophysiological changes and abnormalities in glucose and oxygen metabolism. Digital subtraction angiography remains the gold standard for luminal imaging. The integration of artificial intelligence and machine learning in stroke

imaging interpretation is expanding, serving as decision support tools. Illustrative clinical scenarios demonstrate the application of neuroimaging in evaluating intracerebral hemorrhage, determining eligibility for reperfusion therapies, assessing large vessel occlusions, and characterizing intra- and extracranial stenoses. As treatment options advance, neurologists play a vital role in accurately interpreting neuroimaging studies to guide patient care in the rapidly evolving field of acute stroke management.
Keywords: Radiology, Stroke, diagnosis

Introduction

Neuroimaging has become an increasingly integral component in the diagnosis and management of patients presenting with suspected stroke. Recent advancements in imaging technologies have led to a paradigm shift in acute ischemic stroke (AIS) care, moving away from the traditional time-based criteria for treatment eligibility. Instead, there is now a growing emphasis on tissue- and imaging-based approaches, which allow for more personalized and precise treatment decisions. These shifts underscore the vital role that neurologists play in understanding and interpreting neuroimaging studies, as well as in leveraging artificial intelligence (AI)-based decision support tools to optimize patient outcomes.

The use of neuroimaging in stroke has evolved significantly, with various modalities being employed to assess the extent of brain injury, determine tissue viability, and guide therapeutic interventions. Imaging not only aids in confirming the diagnosis but also provides critical information about the type of stroke, its location, and the underlying vascular pathology. This information is essential for tailoring interventions, whether pharmacologic, such as thrombolysis, or mechanical, such as thrombectomy. In acute settings, imaging-based assessments are increasingly relied upon to identify patients who might benefit from reperfusion therapies even beyond traditional time windows, a shift that has been supported by landmark trials and ongoing research in the field.

In this evolving landscape, the importance of expertise in neuroimaging interpretation cannot be overstated. Neurologists must be adept at analyzing complex imaging findings, often under time-sensitive conditions, to make rapid yet accurate clinical decisions. Furthermore, the integration of AI tools into stroke imaging workflows has added another layer of complexity. These tools are designed to enhance diagnostic accuracy and efficiency by automating processes such as infarct core and penumbra estimation, but their optimal use requires a clear understanding of both their capabilities and limitations.

This review explores the most commonly utilized imaging modalities in the evaluation of stroke patients, including computed tomography (CT), magnetic resonance imaging (MRI), and advanced perfusion imaging techniques. Each modality offers distinct advantages and limitations, and their selection depends on the clinical context, availability, and specific diagnostic questions at hand. Through the inclusion of practical clinical scenarios, we aim to illustrate how these imaging tools can be applied in real-world practice to inform and guide patient care. By doing so, we highlight the critical role of neuroimaging in modern stroke management and underscore the need for continued education and training in this rapidly advancing field.

Computed Tomography

Noncontrast head computed tomography (NCHCT) remains the preferred imaging modality for the initial assessment of patients with suspected stroke. It is widely accessible, cost-effective, rapidly performed, and deployable in mobile stroke units. Advances in CT scanner technology, such as the development of devices with up to 640 detector rows, now enable whole-brain imaging in less than one second. The average effective radiation dose for NCHCT is approximately 2 mSv, with reported values in the literature ranging from 0.9 to 4.0 mSv. Given that the clinical presentations of acute ischemic stroke (AIS) and intracranial hemorrhage (ICH) are often indistinguishable, the high sensitivity of NCHCT for detecting

ICH makes it an essential diagnostic tool. While high-detector scanners represent the latest innovations in imaging technology, standard CT scanners are equally effective for managing acute stroke in most cases. Acute ICH appears hyperdense (bright) compared to normal brain parenchyma on NCHCT, with Hounsfield unit (HU) measurements ranging between 40–60 HU initially and increasing to 60–80 HU within the first few hours. Over time, the attenuation decreases at a rate of −0.7 to 1.5 HU per day. However, NCHCT is less sensitive for identifying subacute or chronic hematomas.

In addition to excluding hemorrhage, NCHCT provides valuable information for patients with AIS, such as evidence of early ischemic changes, chronic infarcts, or the hyperdense artery sign. Within the first six hours of symptom onset, early ischemic changes (EICs) may manifest as loss of gray–white matter differentiation, cortical swelling, or mass effect. As the infarction progresses and becomes irreversible, EICs present as more distinct hypodensities, indicative of cytotoxic edema. The interrater reliability for detecting early infarction signs on NCHCT varies significantly, with reported kappa values ranging from 0.14 to 0.78. The Alberta Stroke Program Early CT Score (ASPECTS), a widely used 10-point scale, aids in the assessment of ischemic changes within the middle cerebral artery (MCA) territory. Adjusting the window width and level to 40/40 on NCHCT enhances contrast visualization of brain parenchyma, facilitating the detection of EICs. Although EICs are not absolute contraindications for reperfusion therapy, extensive ischemic changes are associated with worse outcomes and an increased risk of symptomatic or fatal hemorrhage following thrombolytic therapy. Chronic infarcts, identified as well-defined hypodensities or encephalomalacia within arterial territories, can provide insights into stroke etiology and guide treatment strategies. The hyperdense artery sign, characterized by increased hyperdensity within an artery compared to its normal isodense appearance, is a highly specific indicator of intraarterial thrombus.

Although NCHCT exhibits limited sensitivity for the initial diagnosis of AIS, it has high specificity for detecting irreversible ischemic injury. The sensitivity of NCHCT for identifying infarctions on follow-up imaging ranges from 20% to 87%, depending on image quality and the expertise of the interpreter.

CT Angiography

Computed tomography angiography (CTA) of the head and neck is a rapid and reliable diagnostic tool for evaluating extra- and intracranial occlusive diseases. Technological advancements, such as spiral CT and increased detector arrays, have enhanced image resolution, reduced scan times, and expanded scanning volumes. Faster imaging minimizes motion artifacts and reduces the required contrast dose. The average effective radiation dose for CTA is approximately 5 mSv, with reported values ranging from 0.8 to 20 mSv. The sensitivity and specificity of CTA have been reported as 100% and 63%, respectively, for extracarotid disease, and up to 100% for intracranial disease. Techniques such as maximum intensity projection and 3D reconstructions enable rapid evaluation of clot length, distal stenosis, and leptomeningeal collaterals. Additionally, CTA source images can assist in identifying brain tissue infarction. Areas of reduced contrast enhancement distal to a large vessel occlusion, observable on a 40/40 window setting, likely represent hypoperfused brain tissue at risk of irreversible damage without reperfusion (Sheth et al., 2019). CTA source images correlate strongly with magnetic resonance imaging (MRI) diffusion-weighted imaging and can improve sensitivity and accuracy in estimating final infarct volume (Bal et al., 2015).

CTA should not delay the administration of intravenous thrombolytics, and many stroke protocols recommend initiating intravenous tissue plasminogen activator (IV tPA) prior to performing CTA. Following NCHCT and, if applicable, IV tPA administration, CTA is often used to identify large vessel occlusions in patients who are potential candidates for

endovascular thrombectomy (EVT). The procedure requires adequate intravenous access and normal renal function due to the administration of a contrast bolus. Despite ongoing debate, emerging evidence suggests no significant association between contrast use and acute kidney injury (Brinjikji et al., 2017).

In cases of acute hemorrhagic stroke, CTA is highly effective in diagnosing cerebral aneurysms as small as 2 mm (Yang et al., 2017). It is also valuable for identifying arteriovenous malformations and venous thrombosis. Hematoma expansion within the first three hours occurs in approximately 30% of patients with ICH and is associated with a poor prognosis. The "CTA spot sign," indicating a contrast medium leak hyperdense to the surrounding hematoma, serves as a predictor of hematoma growth, morbidity, and mortality.

CT Perfusion

CT perfusion (CTP) is an advanced imaging technique used to assess cerebral tissue perfusion. Effective radiation doses for CTP range from 1.1 to 5 mSv. While various parameters can be calculated using CTP, the most commonly derived maps include relative cerebral blood flow (rCBF), relative cerebral blood volume (rCBV), time to maximum of residue function (Tmax), and mean transit time (MTT) (Vagal et al., 2019). CTP imaging is performed by administering a bolus of iodinated contrast intravenously, followed by repeated CT scans of the same brain region over time. These scans capture the transit of contrast through the arteries, capillaries, parenchyma, and veins. Based on time–density contrast curves, the aforementioned perfusion parameters are calculated.

In the context of acute ischemic stroke (AIS), CTP is employed to estimate the extent of irreversible brain injury (referred to as the "ischemic core") and the volume of tissue at risk of irreversible injury (termed the "penumbra") (Donahue & Wintermark, 2015). Ischemic core is typically identified through changes in rCBF or rCBV relative to the contralateral hemisphere, while penumbral tissue is often assessed using MTT or Tmax. Relative cerebral blood flow reductions of 30% are commonly used as a threshold to define the infarct core, a measure that has been validated against 24-hour MRI and CT (Demeestere et al., 2020). However, the validation is imperfect, as infarct expansion can occur without timely reperfusion. CBF-based core definitions may overestimate or underestimate the infarct size, particularly in cases of rapid reperfusion after imaging or early presentations of stroke. MTT and Tmax, which measure perfusion delays, are used to evaluate the volume of tissue at risk. The most widely validated threshold for detecting penumbral tissue is Tmax >6 seconds. Software tools such as RAPID, Viz.ai, Olea, GE, Philips, Siemens Syngo, and MIStar automate the derivation of these parameters from raw CTP images. A mismatch ratio, calculated by dividing the penumbra volume (e.g., Tmax >6 seconds) by the core volume (e.g., rCBF <30% relative to the contralateral hemisphere), is used to assess treatment candidacy. Absence of a mismatch suggests that intervention is unlikely to benefit the patient.

Despite rapid advancements in CTP technology, limitations remain, including motion artifacts, partial volume averaging in arterial input and venous outflow regions, and variability in postprocessing techniques. These limitations can lead to discrepancies in parameter maps across different vendors. The necessity of CTP for identifying endovascular thrombectomy (EVT) candidates in both early and delayed time windows is an area of ongoing research.

Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is more sensitive than noncontrast CT (NCHCT) in detecting ischemia at early stages, as well as smaller or posterior fossa lesions. However, MRI is more expensive, less widely available, and contraindicated in certain patients with metallic foreign bodies or older-generation implantable devices. Standard MRI sequences, including T1-weighted, T2-weighted, and fluid-attenuated inversion recovery (FLAIR), are relatively insensitive for detecting hyperacute ischemia. In contrast, diffusion-weighted imaging (DWI) is highly sensitive, specific, and accurate, with reported ranges of 88%–100%, 95%–100%, and

95%, respectively (PhD et al., 2015). DWI reveals early ischemia within minutes as a hyperintense signal caused by restricted water diffusion in brain tissue. The DWI signal is influenced by the Brownian motion of water in tissue, with a linear component from a T2-weighted signal and a brighter signal indicating more restricted diffusibility. Apparent diffusion coefficient (ADC) maps help differentiate true restricted diffusion (DWI bright, ADC dark, T2 bright) from T2 shine-through (DWI bright, ADC bright, T2 bright). The DWI signal peaks at 40 hours and normalizes within two to several weeks, whereas ADC signals peak at 28 hours, pseudonormalize at 10 days, and subsequently become bright. Additional signs of AIS can be observed on other MRI sequences, including absent arterial flow voids on T2, a "blooming" hypointense artery on gradient-recalled echo (GRE) due to acute intravascular thrombus, and intravascular hyperintensity on FLAIR, indicative of slow or collateral flow. GRE or susceptibility-weighted imaging (SWI) sequences are also valuable for detecting acute or chronic hemorrhages and cerebral venous abnormalities, which appear as hypointense signals. In cases of intracerebral hemorrhage (ICH), the MRI signal varies according to hematoma age. Hemorrhage stages are classified as hyperacute (<24 hours, oxyhemoglobin, T1 isointense, T2 bright), acute (1–3 days, deoxyhemoglobin, T1 isointense, T2 dark), early subacute (>3 days, intracellular methemoglobin, T1 bright, T2 dark), late subacute (>7 days, extracellular methemoglobin, T1 bright, T2 bright), and chronic (>14 days, hemosiderin, T1 dark, T2 dark). GRE sequences may overestimate hematoma volume due to amplified signal representation, making it appear larger than the actual blood volume. Subarachnoid and subdural hemorrhages can be readily identified on FLAIR, where cerebrospinal fluid (CSF) signals are suppressed. The hyperintense acute reperfusion marker (HARM) sign, visible on postcontrast FLAIR, indicates early blood-brain barrier disruption and is associated with reperfusion and an increased risk of hemorrhagic transformation, especially after thrombolytic therapy.

Recent studies have demonstrated that MRI can identify AIS patients with unknown time of onset. The WAKE-UP trial randomized patients with restricted diffusion on DWI but no corresponding FLAIR changes to receive intravenous tPA, showing benefit in this cohort relative to placebo (Thomalla et al., 2018). The absence of FLAIR changes in DWI-positive lesions suggests the stroke occurred within six hours.

MRI also provides insights into stroke etiology. In ischemic stroke, involvement of multiple vascular territories or wedge-shaped cortical infarcts may suggest cardioembolic etiology, while border zone infarcts between two vascular territories may indicate arterial stenosis. In hemorrhagic stroke, the presence of lobar, cortical, or corticosubcortical microbleeds or superficial siderosis can suggest cerebral amyloid angiopathy. Additionally, small hematomas within DWI lesions with minimal edema may indicate hemorrhagic transformation rather than primary hematoma formation.

MR Angiography

Magnetic resonance angiography (MRA) is a highly effective diagnostic tool for identifying vessel stenosis or occlusions, though it is more time-intensive than computed tomography angiography (CTA) and not universally available for emergent use around the clock. MRA can serve as an alternative to CTA in acute stroke cases, particularly for patients with contraindications to iodinated contrast, such as those with IV contrast allergies or acute renal failure. It is often employed in the subacute or chronic phases of infarction in conjunction with MRI studies. Given concerns about gadolinium retention in patients with chronic kidney disease or those on dialysis, as well as the risk of nephrogenic systemic fibrosis, MRA of the head and neck can be performed with or without contrast, utilizing the time-of-flight technique in the latter (Do et al., 2020). Contrast-enhanced MRA outlines vascular anatomy using a bolus injection of gadolinium, whereas time-of-flight MRA relies on flow-dependent vascular signals

influenced by the direction and velocity of blood. The latter technique is more susceptible to artifacts and may overestimate stenosis severity.

Despite its limitations, MRA remains competitive with other imaging modalities for diagnosing stenoses, occlusions, and dissections. Studies have demonstrated MRA sensitivity and specificity for carotid occlusions at 100% in most cases. When MRA indicates no stenosis or stenosis below 70%, further diagnostic evaluation is typically unnecessary. Conversely, findings of stenosis greater than 70% warrant additional assessment using modalities such as duplex ultrasonography or conventional angiography. A recent application of contrast-enhanced MRI vascular imaging, black-blood imaging (or spatial presaturation MRI), enhances visualization of vessel walls and their components, such as lipid deposits, fibrous caps, calcium, and thrombus (Al-Smadi et al., 2019). In black-blood MRI, the vessel lumen appears as low signal intensity, allowing better delineation of wall structures. Dissections can be visualized as increased wall signal with lumen narrowing on T1-weighted images with fat suppression and as absent or diminished vessel visualization. False lumens with intimal flaps are most clearly identified on T2-weighted images. In cases of negative MRA but high clinical suspicion, CTA is recommended to confirm or exclude dissections. MRA achieves 95% sensitivity in detecting intracranial aneurysms, though false-positive and false-negative results frequently occur at the skull base and middle cerebral artery (MCA) (Sailer et al., 2014). Sensitivity for detecting aneurysms after subarachnoid hemorrhage ranges from 69%–100%, with specificity of 75%–100%. Smaller aneurysms, particularly those under 5 mm, are more likely to be missed.

MR Perfusion

Magnetic resonance perfusion (MRP), like CTP, generates perfusion maps including relative cerebral blood volume (rCBV), cerebral blood flow (rCBF), time to maximum of residue function (Tmax), and mean transit time (MTT). MRP images are produced within minutes following the bolus injection of gadolinium and acquisition of SWI and T2-weighted sequences. Additionally, arterial spin labeling enables MRP to be conducted without contrast, providing comparable diagnostic information regarding perfusion deficits in acute infarcts, tissue reperfusion after recanalization, and hyperperfusion in subacute infarcts after reperfusion. MRP can identify patients with modest ischemia not meeting the threshold for diffusion-weighted imaging (DWI) positivity by detecting regions of relative hypoperfusion. Moreover, MRI diffusion-perfusion mismatch serves as a criterion for selecting patients for extended reperfusion windows, as demonstrated in the DEFUSE-3 trial (Albers et al., 2018).

MR or CT Venography

MR venography (MRV) or CT venography (CTV) is performed in cases of suspected cerebral venous occlusion. Contrast-enhanced MRV is the preferred imaging method for diagnosing sagittal sinus thrombosis. MRI combined with MRV has a sensitivity of 95% for detecting cerebral venous sinus thrombosis, with MRV specificity varying based on acquisition technique. Recent studies on contrast-enhanced 4D MRV have shown sensitivity and specificity rates of 97% and 99%, respectively. MRV findings indicative of cerebral thrombosis include absent high-flow signals from sinuses and direct visualization of thrombus, such as isolated cortical thrombosis. Venous congestion, infarction, and hemorrhage are also visible on MRI, with hemorrhage appearing consistent with its stage of blood breakdown products. Thrombosed sinuses or veins are detectable on T2- and T1-weighted sequences, with sensitivities of 91% and 71%, respectively.

Noncontrast CT (NCHCT) and CTV are alternative imaging options but are less sensitive for diagnosing cerebral venous thrombosis. On NCHCT, a thrombosed vein or sinus appears hyperdense (the "dense cord" sign), while the "empty delta" sign may be observed on contrast-enhanced NCHCT. However, CTV has limited sensitivity for detecting cortical venous thrombosis.

Optical Coherence Tomography

Optical coherence tomography (OCT) is a minimally invasive, emerging imaging modality that provides high-resolution visualization of intravascular pathology by measuring optical scattering in tissues through low-coherence interferometry (Chen et al., 2018). Despite an imaging depth limited to a few millimeters, OCT delivers significantly higher resolution than ultrasound, achieving micron-level detail in evaluating vascular pathologies involving vessel wall layers. OCT has been successfully applied to assess extracranial pathologies such as atherosclerosis and dissection. As an adjunctive tool during endoluminal stenting, OCT can identify stent apposition, leaks, intraluminal stenosis, thrombosis, neovascularization, ulceration, and lipid deposition. Potential applications include risk stratification for cerebral aneurysms. With advancements in OCT imaging devices and improved safety for intracranial deployment, this modality is expected to play an increasingly prominent role in characterizing intracranial atherosclerotic disease. OCT remains an evolving imaging field with promising applications in endovascular visualization.

Ultrasonography

Ultrasonography remains the preferred noninvasive method for real-time assessment of cerebral blood flow. Techniques such as duplex ultrasonography and transcranial Doppler ultrasonography (TCD) are cost-effective, widely accessible in many healthcare settings, and safe due to the absence of radiation and contrast usage. However, ultrasonography is highly operator-dependent, and its diagnostic accuracy can vary significantly among imaging facilities. The method relies on backscattering or reflection of sound waves from tissues with differing acoustic properties, which are detected by the ultrasound probe. Images are generated using brightness-modulated (B-mode) techniques, which evaluate the amplitude of sequentially returning echoes. These echoes are rendered as grayscale images, where bright (strong) or dark (weak) regions correspond to the depth and intensity of the reflections. Blood flow visualization is facilitated through color-coded Doppler flow imaging within the B-mode framework. Additional imaging techniques, such as B-flow, harmonic imaging, Doppler velocity spectral display, and 3D ultrasonography, further enhance vessel examination and pathology evaluation.

Ultrasonography has extensive diagnostic and therapeutic utility. It is frequently used to evaluate extracranial carotid stenosis and analyze plaque morphology. The degree of stenosis is assessed using parameters such as peak systolic velocity, end-diastolic velocity (EDV), and the systolic internal carotid artery/common carotid artery velocity ratio measured via B-mode ultrasound. Dissections and inflammatory conditions, including Takayasu arteritis, affecting both anterior and posterior circulations can also be identified and monitored using ultrasonography.

In acute stroke scenarios, ultrasonography provides real-time data on stenosis, occlusions, and collateral circulation, as well as monitoring vasomotor reactivity, embolization, and recanalization after thrombolytic therapy. Advanced techniques, such as vasomotor reactivity testing, emboli detection, and right-to-left shunt detection, aid in identifying stroke mechanisms, tailoring treatment, and determining prognosis. TCD is particularly effective for detecting and monitoring vasospasm following subarachnoid hemorrhage, tracking elevated intracranial pressure through waveform analysis, and confirming cerebral circulatory arrest. Emerging applications, including high-frequency ultrasound and microbubble-enhanced sonolysis, show promise in augmenting thrombolysis effectiveness and achieving recanalization without thrombolytic agents (Saqqur et al., 2014). Ongoing research is exploring the potential of ultrasound for disrupting the blood-brain barrier, enhancing gene therapy delivery, and facilitating targeted drug delivery.

Positron Emission Tomography/Single-Photon Emission Computed Tomography

Positron emission tomography (PET) and single-photon emission computed tomography (SPECT) are nuclear medicine imaging techniques that have significantly advanced stroke research. PET enables the assessment of pathophysiological changes during ischemia by measuring physiological parameters and visualizing the distribution of molecular markers. In stroke, 15O-labeled water PET provides valuable insights into the progression from the penumbra to ischemic tissue, revealing abnormalities in glucose and oxygen metabolism. Radioligands serve as early indicators of irreversible tissue damage, allowing for prediction of final infarct size. PET is also employed to evaluate cerebral blood flow (CBF) reserve capacity in carotid atherosclerotic disease, which aids in planning future interventions.

SPECT, using an acetazolamide challenge, assesses diminished vascular reserve and predicts ischemia development in patients undergoing endarterectomy. Additionally, SPECT can characterize the content of atherosclerotic plaques, including oxidized low-density lipoprotein and apoptotic bodies. Reperfusion can also be confirmed through nuclear imaging studies. Moreover, PET provides detailed information on metabolic and molecular changes associated with neuroinflammation following stroke.

Digital Subtraction Angiography

Digital subtraction angiography (DSA) remains the definitive gold standard for luminal imaging, offering unparalleled spatial and temporal resolution for assessing cervical and cerebral circulation. This modality enables neurointerventionalists to make precise diagnoses and customize treatments such as revascularization, angioplasty, stenting, and coiling for individual patients. Large studies indicate an approximate 1% procedural risk for complications such as stroke, dissection, puncture site issues, and iodine-related renal dysfunction. However, limitations of DSA include its operator-dependent image quality, limited availability, and high cost. Other articles within this issue delve further into DSA's role in stroke management.

Artificial Intelligence/Machine Learning

Artificial intelligence (AI) has increasingly impacted medical imaging, with acute stroke representing one of its earliest and most significant applications. The primary challenge in acute stroke imaging interpretation is the need for immediate, expert-level assessments available 24/7 at all facilities treating stroke patients. The current shortage of human resources to meet this demand is expected to intensify as the treatment windows for thrombolysis and endovascular therapy (EVT) expand. Machine learning (ML) offers a promising solution by serving as a decision support tool to assist neurologists, drawing attention to relevant imaging regions and providing diagnostic suggestions (Murray et al., 2020).

ML algorithms are already in widespread and growing use for assessing EVT eligibility (Nagel et al., 2017). Several software platforms, such as eASPECTS (Brainomix), RAPID (IschemaView), and Viz.ai, offer automated CT analysis, generating color-coded maps of ischemic core and penumbra alongside angiographic vessel assessments. These algorithms reliably identify the presence or absence of large vessel occlusions (LVO) and estimate infarction extent from CTA data. AI applications extend to acute prognosis predictions, including the risk of intracerebral hemorrhage (ICH) (Bentley et al., 2014). As the number of patients evaluated for acute stroke therapies increases, the role of ML in imaging interpretation is expected to expand significantly.

Illustrative Clinical Scenarios

Evaluation of ICH

In many centers, including mobile stroke units, non-contrast head CT (NCHCT) remains the initial imaging modality for evaluating patients with suspected acute stroke. Its rapid acquisition and high sensitivity for acute ICH enable timely administration of thrombolytic therapy in eligible patients, as normal NCHCT findings effectively exclude ICH. In cases where ICH is identified NCHCT provides additional diagnostic information. The hemorrhage pattern and location can suggest the underlying etiology. For example, hypertensive

hemorrhages typically occur in predictable regions such as the pons, cerebellar nuclei, basal ganglia, and thalamus. Hemorrhages in atypical locations may be associated with vascular malformations, amyloid angiopathy, or other causes.

Additional imaging modalities such as MRI and CTA can help identify underlying conditions, including arteriovenous malformations, cerebral aneurysms, cavernous malformations, hemorrhagic tumors, and other etiologies. CTA is particularly useful for predicting hematoma expansion. However, these additional techniques are not fully sensitive for excluding alternative causes, and further imaging—such as CTV, MRV, DSA, or follow-up MRI—may be required to complete the diagnostic evaluation.

Acute Decision-Making for Thrombolysis and Thrombectomy

The management of acute ischemic stroke (AIS) has evolved significantly in recent years, particularly concerning eligibility for reperfusion therapies such as thrombolysis and mechanical thrombectomy. Neuroimaging increasingly guides treatment decisions, replacing traditional time-based criteria, especially for mechanical thrombectomy, with potential implications for thrombolysis as well.

NCHCT remains the only imaging modality required before administering intravenous recombinant tissue plasminogen activator (IV rtPA), as it reliably excludes ICH (Powers et al., 2019). While ancillary imaging, such as MRI, can provide additional insights (e.g., identifying microhemorrhages and assessing post-tPA hemorrhage risk), current guidelines do not recommend its routine use for this purpose. Similarly, the routine use of CTP and magnetic resonance perfusion (MRP) imaging before treatment is not advised, given the highly time-dependent efficacy of thrombolysis.

After thrombolysis eligibility is determined and treatment administered, mechanical thrombectomy becomes the next consideration. NCHCT retains a vital role in this process, as experienced observers can reliably detect areas of irreversible injury. Quantified scoring systems based on NCHCT data strongly correlate with 90-day clinical outcomes following thrombectomy (Yoo et al., 2014).

CTA is an effective subsequent imaging study for identifying intracranial occlusions. Although its necessity has been debated, earlier studies demonstrated that patients with a National Institutes of Health Stroke Scale (NIHSS) score ≥10 had an 80% likelihood of harboring an intracranial occlusion. This approach was employed in the IST-3 trial, where 89 of 434 patients (21%) randomized to endovascular therapy did not undergo thrombectomy, often due to the absence of an accessible thrombus. Current guidelines from the American Heart Association/American Stroke Association (2019) recommend noninvasive vascular imaging, such as CTA, as part of the initial imaging evaluation for patients meeting clinical criteria (Powers et al., 2019).

Evaluation of Large Vessel Occlusion for Endovascular Therapy

When assessing patients with large vessel occlusion (LVO) for potential benefits from endovascular therapy (EVT), a key consideration is the size of the ischemic core and the extent of the penumbra. Computed tomography perfusion (CTP) imaging has become an increasingly utilized tool to evaluate these factors, using calculated maps based on the transit of contrast through cerebral tissue. Automated postprocessing software and strict volume-based cutoff criteria have been employed to identify patients who can benefit from endovascular reperfusion, as demonstrated in the DAWN and DEFUSE-3 trials (Nogueira et al., 2018), even many hours after symptom onset. However, it is essential to recognize that some patients not meeting these criteria may still derive benefit and that predicted ischemic core and penumbra regions may occasionally yield inaccuracies in an unpredictable manner (Boned et al., 2017; Lee et al., 2019).

The primary goal of treating LVO patients with salvageable tissue is to achieve rapid revascularization. Ideally, the final infarct volume should closely align with the initially predicted ischemic core.

Evaluation of Carotid Stenosis

Extracranial carotid artery stenosis is one of the few stroke etiologies that can be directly treated surgically, with imaging playing a central role in diagnosis and determining treatment eligibility. The infarction pattern visible on MRI can provide etiological insights; for instance, infarctions in the middle cerebral artery (MCA) and anterior or posterior cerebral artery border zones are frequently associated with vascular stenosis. Despite advancements in understanding plaque morphology and associated risks of recurrent stroke based on atheroma composition, guidelines for revascularization and reimbursement remain tethered to imaging-based stenosis measurements for both symptomatic and asymptomatic cases (Abbott et al., 2015).

Noninvasive imaging techniques, such as CTA, now provide highly accurate and visually interpretable depictions of carotid stenosis, often mirroring findings observed in DSA, the gold standard.

Evaluation of Intracranial Stenosis

Intracranial vessel stenosis has a wide range of potential etiologies, including inflammatory conditions (e.g., vasculitis), atherosclerosis, moyamoya syndrome, dissection, and others. Imaging is essential for diagnosing and understanding the physiological implications of these conditions. Infarction related to intracranial stenosis may result from hypoperfusion distal to the stenosis, occlusion of a branch vessel within the stenotic region, or downstream thromboembolism originating from the area of vascular injury.

Hypoperfusion-related symptoms may present transiently or persistently, indicating regional cerebral dysfunction without definitive evidence of infarction on conventional imaging during the acute phase. Contrast-enhanced MRI techniques that focus on the vessel wall can reveal thickening and enhancement in the affected or adjacent areas, aiding in differential diagnosis. DSA remains the gold standard for assessing intracranial luminal compromise due to its superior spatial and temporal resolution. More importantly, DSA can also evaluate downstream cerebral blood flow (CBF) changes.

Because cerebral perfusion is dynamic, clinical symptoms may fluctuate, and perfusion studies that capture a single time point, such as CTP, can overestimate or underestimate hypoperfusion. Dynamic imaging techniques incorporating cerebrovascular reserve challenges can better define brain regions at risk of ischemia. SPECT imaging with acetazolamide, a relatively accessible modality, is one such approach. Baseline images are compared with post-acetazolamide images, allowing qualitative assessment of radionuclide uptake changes. SPECT has been validated against gold-standard O-15-H2O PET for patients with cerebrovascular stenotic disease.

Modern neuroimaging continues to enhance the ability to assess tissue viability and predict outcomes with greater precision. These advancements have led to the expanded use of thrombolysis and thrombectomy in larger patient populations. As treatment options grow, the neurologist's role in rapidly and accurately interpreting neuroimaging studies becomes increasingly vital.

Conclusion

Radiology imaging has become an indispensable tool in modern stroke diagnosis and treatment, evolving significantly with advancements in technology and techniques. Modalities such as computed tomography, magnetic resonance imaging, digital subtraction angiography, and ultrasonography play pivotal roles in assessing stroke type, location, and underlying vascular pathology. Additionally, emerging technologies like artificial intelligence and machine learning are transforming stroke imaging by enhancing diagnostic precision and enabling rapid decision-making in acute care settings.

Despite the progress, challenges remain in optimizing imaging use across diverse clinical scenarios, improving accuracy in ischemic core and penumbra prediction, and ensuring broader access to advanced modalities. As neuroimaging techniques continue to advance, the integration of these tools into clinical practice will depend on comprehensive education, interdisciplinary collaboration, and ongoing research to refine their applications. Ultimately, the combination of cutting-edge radiology imaging and clinician expertise will continue to drive improvements in patient outcomes for stroke and related neurovascular conditions.

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