State of the Art Stroke Imaging: A Current Perspective

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Abstract
Acute stroke is a widespread, debilitating disease. Fortunately, it also has one of the most effective therapeutic options available in medicine, endovascular treatment. Imaging plays a major role in the diagnosis of stroke and aids in appropriate therapy selection. Given the rapid accumulation of evidence for patient subgroups and concurrent broadening of therapeutic options and indications, it is important to recognize the benefits of certain imaging technologies for specific situations. An effective imaging protocol should: 1) be fast, 2) easily implementable, 3) produce reliable results, 4) have few contraindications, and 5) be safe, all with the goal of providing the patient the best chance of achieving a favorable outcome. In the following, we provide a review of the currently available imaging technologies, their advantages and disadvantages, as well as an overview of the future of stroke imaging. Finally, we offer a perspective.

Résumé
L'accident vasculaire cérébral aigu est une maladie courante et invalidante. Heureusement, il bénéficie aussi de l'une des options thérapeutiques les plus efficaces disponibles en médecine : le traitement endovasculaire. L'imagerie joue un rôle majeur dans le diagnostic de l'AVC et aide à choisir le traitement le mieux adapté. Compte tenu de la rapide accumulation de données probantes concernant des sous-groupes de patients et l'élargissement simultané des options et indications thérapeutiques, il est important d'identifier les avantages de certaines technologies d'imagerie pour des situations spécifiques. Un protocole d'imagerie efficace doit : 1) être rapide, 2) être facile à mettre en œuvre, 3) produire des résultats fiables, 4) avoir peu de contre-indications, et 5) être sans danger, le tout dans le but de donner au patient les meilleures chances d'obtenir une issue favorable. Nous offrons dans ce qui suit une revue des technologies d'imagerie actuellement disponibles, leurs avantages et inconvénients, ainsi qu'une vue d'ensemble du futur de l'imagerie de l'AVC. Pour conclure, nous offrons notre point de vue à ce sujet.

Keywords
acute stroke, diagnostic imaging, computed tomography, evidence-based medicine, endovascular treatment

Acute ischemic stroke (AIS) is a widespread, debilitating disease, globally affecting approximately 9.5 million people per year.1 In the US and Canada, it is a leading cause of death and disability.2 Fortunately, it also has one of the most effective therapeutic options available in medicine, endovascular treatment (EVT), with an astonishingly low number needed to treat of 2.6 for patients with large vessel occlusions (LVO).3 Prior to EVT, intravenous (IV) thrombolytics comprised the standard of care and, currently, if patients are eligible, both are often used in combination to achieve and maintain vessel patency.4

The AIS population is heterogenous, however in the Canadian-led HERMES meta-analysis of the large EVT trials5-9 (one of which was also Canadian-led), the investigators did not identify any subgroups in which the treatment was not effective.10 These initial trials, however, involved highly selected patient cohorts and were thus able to show a clear benefit, albeit at the cost of excluding many patients who may have benefited from treatment.2,11 Since then, many trials have been done or are being conducted on patients who fall outside of these strict inclusion criteria. The BASICS (ClinicalTrials.gov Identifier: NCT01717755) and BEST12 trials examined the effect of EVT on vertebrobasilar occlusions versus best medical management and found no significant difference in patient outcome, in contrast to a registry-based...
EVT of tandem occlusions may be reasonable COR IIb; LOE B-R

EVT is reasonable for patients with AIS due to LVO presenting between 6 - 24 hours of last known well who
EVT is recommended for patients with AIS due to LVO presenting between 6 - 16 hours of last known well
EVT may be reasonable for patients with AIS due to LVO when treatment can be initiated
EVT may be reasonable for patients with AIS due to occlusion of the M2 and M3 segments, the ACA*, the
Patients should receive EVT if they meet the following criteria: (1) pre-stroke mRS score of 0 to 1; (2) causative
For EVT eligible patients, an initial vascular imaging study is recommended, but should not delay IV
Advanced imaging (e.g., perfusion) in patients presenting in <6 hours is not recommended for EVT selection COR III No benefit; LOW B-R
Potential candidates for EVT should receive imaging of the intracranial circulation as well as extracranial carotid
Table 1. Imaging-Related Guideline Recommendations.4,21

| Recommendation                                                                 | Level of evidence       |
|--------------------------------------------------------------------------------|-------------------------|
| Imaging studies should be performed within 20 minutes of arrival in the ED in at least 50% of patients who are potential candidates for IV thrombolysis and/or EVT | COR II; LOE C-EO       |
| Potential candidates for EVT should receive imaging of the intracranial circulation as well as extracranial carotid and vertebral arteries to aid in EVT procedure planning | COR II; LOE B-R         |
| Advanced imaging (e.g., perfusion) in patients presenting in <6 hours is not recommended for EVT selection | COR III No benefit; LOW B-R |
| For EVT eligible patients, an initial vascular imaging study is recommended, but should not delay IV thrombolysis if indicated. | COR I; LOE A            |
| EVT may be reasonable for patients with AIS due to occlusion of the M2 and M3 segments, the ACA*, the PCA*, or the vertebrobasilar arteries* where treatment can begin within 6 hours of symptom onset | COR IIb; LOE B-R        |
| EVT may be reasonable for patients with AIS due to LVO when treatment can be initiated ≤6 hours of symptom onset and pre-stroke mRS >1, ASPECTS <6, or NIHSS score <6. Additional trial data required. | COR IIb; LOE C-EO        |
| EVT is recommended for patients with AIS due to LVO presenting between 6 - 16 hours of last known well who meet the DAWN or DEFUSE 3 criteria | COR II; LOE A            |
| EVT is reasonable for patients with AIS due to LVO presenting between 6 - 24 hours of last known well who meet the DAWN eligibility criteria | COR IIa; LOE B-R         |
| EVT of tandem occlusions may be reasonable | COR IIb; LOE B-R         |

COR: class of recommendation (I: strong benefit, IIa: moderate; IIb weak; III: no benefit/harm); LOE: level of evidence (A: high quality, B-R/B-NR: moderate quality; C-LD: studies with limitation of design or execution; C-EO: consensus of expert opinion); EVT: endovascular treatment; mRS: modified Rankin scale; NIHSS: National Institutes of Health Stroke Scale; ASPECTS: Alberta Stroke Program Early CT Score; ACA: anterior cerebral artery; PCA: posterior cerebral artery; M2/ M3: second and third segments of the middle cerebral artery; LVO: large vessel occlusion

However, both trials were relatively small and limited to crossover, and there was no evidence of a detrimental effect of EVT. The late window trials DAWN and DEFUSE 3 used CTP and MRI-based imaging criteria to show the efficacy of EVT in patients presenting beyond the 6-hour time window,14,15 which have been adopted in many clinics around the world. Recently, the focus has shifted to medium vessel occlusions (MeVOs); data from non-randomized studies suggest that EVT of MeVOS is both possible and safe,16-18 however high-level evidence from randomized trials is lacking. Furthermore, trials investigating the effect of EVT on outcome in patients with large baseline infarctions and minor stroke are currently underway (SELECT-2 (ClinicalTrials.gov Identifier: NCT03876457), TESLA (ClinicalTrials.gov Identifier: NCT03805308), TENSION (ClinicalTrials.gov Identifier: NCT03094715), LASTE (ClinicalTrials.gov Identifier: NCT03811769) and MOSTE (ClinicalTrials.gov Identifier: NCT03796468)). Researchers often use the term “futile treatment” when referring to EVT that did not lead to an improvement in outcomes, and patient selection criteria are applied to identify patients who are most likely to benefit from EVT, thereby also aiming to keep the “futile” EVT procedures at a minimum. This approach is however problematic, since the decision to treat or not to treat with EVT is made based on available information prior to treatment, and there are several factors after the treatment decision has been made that also influence outcomes, such as reperfusion quality, stroke unit care, and post-stroke complications. Even in cases in which EVT does not lead to an improvement in outcome, the complication rate of the EVT procedure appears to be low and there is no evidence of harm in patients with failed EVT compared to those who are not treated with EVT.20 A synopsis of the current American and Canadian evidence-based imaging-related guideline recommendations can be found in Table 1.

While EVT is highly effective in (re)-opening the vessel, it must be done in a timely manner. Indeed, an estimated 2 million neurons die for every prolonged minute of vessel occlusion, highlighting the acute, time critical nature of this disease (“time is brain”).22 As such, it is crucial to minimize the steps between stroke onset and recanalization.

Acute stroke due to non-traumatic hemorrhage represents 10-15% of all stroke cases, however is associated with higher rates of mortality and morbidity.23 Imaging plays a major role in the differentiation of diagnosis between AIS and stroke due to hemorrhage and thereby aids in the triage of patients for appropriate therapy selection. It has evolved rapidly over the years, from a simple non-contrast computed tomography (NCCT) scan performed within a week of onset to sophisticated software programs that allow for quasi-immediate automatic brain parenchyma assessment and detection of the occluded vessel. These technological developments are iteratively occurring within an adaptive framework in response to broadening therapeutic indications. At the same time, there has been an increase in imaging technology accessibility, allowing diagnostic stroke workups to be performed at smaller tertiary or more rural clinics. As a result, multiple imaging strategies exist, largely dependent on institutional resources, regional guideline recommendations, and, to some extent, stroke physician preferences. Regardless, the goal has remained the same:
to quickly diagnose and appropriately treat the patient for the best chance of achieving a favorable outcome.

**Goals of Imaging in Acute Stroke**

When a patient presents to the emergency department with suspected stroke, neuroimaging is paramount to confirm the diagnosis and helps physicians to make timely treatment decisions by excluding the presence of hemorrhage or other stroke mimics, visualizing the occlusion site, and assessing the extent of tissue damage/ischemic changes. All this information is necessary for appropriate patient triage and therapy selection, which is arguably the most important role of neuroimaging in stroke. To this end, most AIS imaging protocols include parenchymal imaging, vascular imaging, and some form of functional imaging to assess for irreversibly damaged versus potentially salvageable tissue (i.e., so-called “core” versus penumbra); otherwise described as the assessment of the 3 Cs: core, clot, collaterals.

### Table 2. Advantages and Disadvantages of Various Acute Stroke Protocols.

| NCCT + spCTA | NCCT + mCTA |
|--------------|-------------|
| **Pros**     | **Pros**    |
| NCCT:        | NCCT:       |
| Widely available | Equivalent mCTA: |
| Cheap        | Advantages of spCTA, plus: |
| Fast         | Improves detection of LVO and MeVO (e.g., with color coded vessel maps) |
| Easy to use  | Can help distinguish between pseudo-occlusion and true carotid occlusion |
| Standardized score for extent of ischemia (ASPECTS) | mCTA-based collateral status is predictive of patient outcome following EVT |
| Allows selection for IV thrombolysis (hemorrhage exclusion) | mCTA-tissue maps provide information on tissue perfusion status, but with less radiation, time, and contrast than CTP |
| spCTA:       | NCCT:       |
| Provides accurate information of the extracranial and intracranial vasculature for procedural planning | Equivalent |
| Can identify underlying pathology (dissection/atherosclerosis/AVM) | spCTA: |
| NCCT: Lacunar infarcts/those in the posterior fossa can be difficult to visualize | Equivalent |
| Ischemic changes <3.5 hours from onset may not be visible | mCTA: |
| MeVOs are overlooked in up to one third of patients on spCTA |
| **Cons**     | **Cons**    |
| NCCT:        | NCCT:       |
| NCCT: Equivalents |
| spCTA:       | mCTA:       |
| Equivalent   | Advantages of spCTA, plus: |
| NCCT:        | Improves detection of LVO and MeVO (e.g., with color coded vessel maps) |
| spCTA:       | Can help distinguish between pseudo-occlusion and true carotid occlusion |
| NCCT:        | mCTA-based collateral status is predictive of patient outcome following EVT |
| spCTA:       | mCTA-tissue maps provide information on tissue perfusion status, but with less radiation, time, and contrast than CTP |

| NCCT + CTA + CTP | MRI |
|-------------------|-----|
| **Pros**          | **Cons** |
| NCCT:             | No radiation exposure |
| Equivalent        | Gadolinium-based contrast generally well tolerated |
| spCTA:            | Highly sensitive for early ischemic changes |
| Equivalent        | TOF angiography: |
| CTP:              | Can be done without contrast⁸ |
| Helpfull in locating the site of occlusion, particularly for trainees | MRI: |
| NCCT:             | Less available |
| Equivalent        | More expensive |
| spCTA:            | Longer scan times |
| Equivalent        | Contraindications (implants, claustrophobia) |
| CTP:              | TOF angiography: |
| Lack of standardization/differences in post-processing software algorithms²⁵ | Less accurate |
| Results dependent on patient factors | Susceptible to motion artifacts |
| Possible overestimation of core²⁶ | Slow flow can lead to signal dropout |
| Principle of “garbage in, garbage out”: if the patient is restless, motion artifacts can make CTP uninterpretable²⁷ | Intracranial and extracranial vasculature is not captured in one sequence |
| Tissue may be hypodense on NCCT but, if reperfusion has (spontaneously) occurred, there may be no perfusion deficit | |

CT: computed tomography; CTA: computed tomography angiography; NCCT: non-contrast CT; spCTA: single phase CTA; mCTA: multiphase CTA; CTP: CT perfusion; MRI: magnetic resonance imaging; ASPECTS: Alberta Stroke Program Early CT Score; AVM: arteriovenous malformation; MeVO: medium vessel occlusion; LVO: large vessel occlusion; EVT: endovascular treatment; TOF: time of flight

⁸Often cited as an advantage over iodinated contrast CTA-studies, however a meta-analysis could not detect an increase of acute kidney injury in patients who received contrast²⁸
In addition, acute stroke imaging findings can also help predict outcomes following treatment and may guide further patient management in the early post-acute phase, e.g., by identifying potential sources of stroke or underlying vessel pathology. While CT remains the fastest and most widely available imaging modality, magnetic resonance imaging (MRI) is also employed for the AIS workup, particularly for certain patient subgroups (e.g., those presenting in the late time window). As in many aspects of medicine, there is no one-size-fits-all strategy; each step of the decision pathway, including choice of imaging, is based on a culmination of factors, including local resources. However, from our own experience, it is useful to standardize acute stroke imaging within one institution so that the physicians on call and imaging technicians know exactly what to do, which streamlines workflows and avoids confusion and subsequent time delays.

In the following, we present an overview of the currently available state-of-the-art stroke imaging modalities, their advantages and disadvantages (Table 2), and their role in acute treatment decision-making, outcome prognosis, and post-acute management. Due to the in our opinion limited applicability of MRI for the acute stroke situation, we have placed the focus on CT-based protocols. We also provide a brief discussion on the future of stroke imaging technology and how that could impact our current protocols and practices.

**Imaging Techniques Used for Treatment Decision-Making in Acute Ischemic Stroke**

1. Parenchymal Imaging

The information needed for treatment decision-making that can be obtained from parenchymal imaging includes a) exclusion of intracranial hemorrhage (ICH), and b) exclusion of extensive ischemic changes (usually assessed with the Alberta Stroke Program Early CT Score [ASPECTS], Figure 1), as both these findings would preclude treatment with IV thrombolysis and EVT.

**CT Based**

As previously mentioned, NCCT remains the primary imaging modality for the diagnosis of AIS. It is fast, widely available, and allows for easy imaging of critically ill patients. Furthermore, CT scanners are improving, producing higher-quality images at lower radiation doses.

**Exclusion of intracranial hemorrhage:** NCCT can rule out the presence of ICH with almost 100% accuracy, which is a...
for detecting lacunar infarcts or those within the posterior fossa. While a lacune may not be of immediate relevance for the emergent AIS situation, suspected occlusion of the vertebrobasilar circulation could represent a rare instance where MRI is the preferred diagnostic modality.

In patients presenting in the >4.5-hour time window or those with unknown time of onset, fluid-attenuated inversion recovery (FLAIR)/DWI mismatch is commonly used to determine eligibility for IV thrombolytics.

**Vascular Imaging**

The information needed for treatment decision-making that can be obtained from vascular imaging includes a) identification of a vessel occlusion and its location, since this will decide whether a patient is amenable for EVT or not, and b) assessment of the aortic arch and cervical arteries, which is important for the choice of access site and appropriate devices in case EVT is performed. For hemorrhagic stroke, vascular imaging is useful for the detection of underlying pathology.

**CT Based**

CT angiography (CTA) provides an iodine contrast-based visualization of the cerebral and cervical vasculature, usually from the aortic arch to the vertex.

**Identifying the occlusion site:** Conventional CTA has a sensitivity and specificity of more than 98% for LVO detection, with high inter-rater agreement. However, medium vessel occlusions (MeVOs), such as occlusions of the M2 segment of the middle cerebral artery, are overlooked in up to one third of patients when using conventional (single-phase) CTA. Multiphase CTA (mCTA) is a well-established and validated Canadian-developed time resolved technology that has been shown to be superior to single-phase CTA for collateral assessment, a known predictor of outcome after EVT. It involves acquisition of an initial arterial phase from the aortic arch to the vertex, followed by 2 late arterial and early venous phases from the skull base to the vertex, with a minimal increase in radiation dose (Figure 2). mCTA improves detection of LVO and medium vessel occlusions (MeVO) in comparison to conventional (single-phase) CTA (“delayed vessel sign”), particularly important for the latter due to their smaller vessel caliber and more distal location from the arterial tree.

**Assessment of the extracranial vasculature:** CTA covers the cervical arteries and the aortic arch, thereby providing useful information about EVT access, such as sharp kinks or heavily calcified plaques that would render endovascular access more challenging and require special equipment such as ultra-stiff wires. In cases of tandem or carotid terminus occlusions, parallel assessment of the 3 phases of the mCTA can help distinguish between extracranial carotid pseudo-occlusion due to reduced flow rates and true extracranial carotid occlusion, which is important for therapeutic decision making and endovascular device choice. CTA also reliably identifies potential underlying pathologies such as atherosclerosis and

**MRI Based**

In some cases (and if available), MRI-based imaging can be advantageous over CT, despite longer acquisition times (MRI has been shown to delay door to needle times in a quasi-randomized trial) and more complex monitoring systems. For example, when the NCCT is negative, yet the clinical suspicion of AIS remains high.

**Exclusion of intracranial hemorrhage:** Gradient echo and susceptibility weighted MRI can detect small hemorrhagic foci and microbleeds (a potential sign of cerebral amyloid angiopathy) with high sensitivity, which can guide thrombolytic therapeutic decision making.

**Exclusion of extensive ischemic changes:** Diffusion weighted MR imaging (DWI-MRI) visualizes cytotoxic edema and is positive within minutes of stroke onset. It can be useful
Dual energy CT-enabled post processing (e.g., bone removal) can be particularly useful for imaging vessels that are close to or obscured by bony structures, such as posterior circulation occlusions.

Assessment of underlying pathology in hemorrhagic stroke: in the case of lobar hemorrhage, CTA can identify possible etiologies such as vascular malformations or cerebral venous thrombosis. Furthermore, the spot sign, i.e., contrast extravasation within the hemorrhage, represents one of the most promising predictors of hematoma expansion.

**Advanced Imaging for AIS**

The goal of functional imaging in AIS at baseline is to assess the extent of ischemic core and the “penumbra” (tissue at risk, which is not yet irreversibly damaged and would benefit from reperfusion). The current belief is that immediate reperfusion saves penumbral tissue, but not core, and reperfusing the latter therefore does not result in improved outcomes but may cause harm due to an increased risk of reperfusion hemorrhage. The current practice is to proceed with treatment when there is a small ischemic core and a large penumbra (“target mismatch profile”) and to forego treatment when a large core and little or no penumbra is present.

**CT based**

**mCTA**. mCTA displays pial-arterial collateral filling in a time-resolved fashion, which can be translated into a 3-point score (good vs. intermediate vs. poor collaterals) (Figure 2). mCTA collateral status is predictive of patient outcome following EVT, as was shown in the ESCAPE trial; patients with good mCTA collaterals...
were more likely to benefit from EVT, even if the ASPECTS was low.\textsuperscript{55} mCTA collateral status also predicts outcome following IV thrombolysis.\textsuperscript{56} mCTA is robust and easy to implement; however, extracranial carotid stenosis and cardiac failure can lead to an underestimation of collaterals.\textsuperscript{45} Collateral scoring on conventional mCTA requires simultaneous/side-by-side reading of all 3 phases, which assumes a certain level of expertise. To facilitate mCTA readings, a novel display format has been developed in which time variant color maps are superimposed to create a single image (Figure 3).\textsuperscript{57} These have been shown to further improve prediction outcome in patients with AIS due to LVO compared to conventional mCTA collateral grading.\textsuperscript{58}

**CT perfusion maps.** During CT perfusion (CTP), the brain is scanned multiple times after administration of a bolus of IV contrast. Manufacturer-specific software algorithms then produce color coded output maps that reflect hemodynamics and changes in cerebral blood volume (CBV) in comparison to the contralateral, unaffected side. These most commonly include mean transit time (MTT), cerebral blood flow (CBF), time to maximum (Tmax), and CBV, and rely on the central volume principle of CBF = CBV/MTT.\textsuperscript{59} Together, they help to identify the site of vessel occlusion, as well as unmask ischemic changes that are not immediately visible on the NCCT, both of which can be particularly useful for trainees. CTP-derived parameters like the hypoperfusion intensity ratio (HIR) can also give an estimate of the collateral status. HIR is defined as the ratio of volume with a Tmax greater than 10 seconds (i.e., severe hypoperfusion) to the volume of tissue with a Tmax greater than 6 seconds\textsuperscript{60} and has been used to estimate the infarct progression rate for decision making in potential transfer scenarios.\textsuperscript{61}

NCCT, CTA, and CT perfusion (CTP) now comprise the “state-of-the-art-advanced imaging” protocol of many stroke centers. Whole brain CTP is used to estimate “core” and penumbra volume, which aids in patient selection for EVT, particularly those with an onset or last known well of greater than 6 hours.\textsuperscript{4,14,15} Importantly, CTP is not necessary for clinical decision-making in patients presenting within 6 hours from last known well and obtaining CTP should never delay IV thrombolysis or EVT.
The disadvantages of CTP are partially a result of the longer acquisition, processing, and interpretation times. Furthermore, CTP represents a snapshot in time and is dependent on patient cardiac function and blood pressure. Concomitant extracranial carotid stenosis can lead to hypoperfusion of the supplied hemisphere and result in under/overestimation of the core and penumbra, respectively. Previous infarcts and white matter disease can also confound the results.

Postprocessing algorithms employ varying thresholds to display the degree of mismatch between infarct core and penumbra, by providing volumes for each that could give the readers a false sense of precision. Brain tissue with CBF values ≤5 mL/100 g/min have been shown to regain function if reperfusion is rapidly achieved. As a result, these measures are at most a probabilistic estimate of tissue that will proceed to infarction if the vessel is not recanalized, otherwise previously referred to as severe ischemic tissue of unknown viability (sit-UV).

An alternative to perfusion-like imaging can be achieved with mCTA-derived tissue maps. Since mCTA allows for whole brain time resolved images of the pial vessels, information on tissue perfusion status can be extracted using a discrete 4-point time intensity curve. These maps are similar to conventional CTP maps (Figure 4), but require a substantially lower radiation dose, less contrast, and do not result in prolonged imaging times. A recent study by Wu et al observed that mCTA-based perfusion models were able to predict infarct core, penumbra, and perfusion status using machine learning, with comparable accuracy to CTP.

**mCTA tissue maps.** An alternative to perfusion-like imaging can be achieved with mCTA-derived tissue maps. Since mCTA allows for whole brain time resolved images of the pial vessels, information on tissue perfusion status can be extracted using a discrete 4-point time intensity curve. These maps are similar to conventional CTP maps (Figure 4), but require a substantially lower radiation dose, less contrast, and do not result in prolonged imaging times. A recent study by Wu et al observed that mCTA-based perfusion models were able to predict infarct core, penumbra, and perfusion status using machine learning, with comparable accuracy to CTP.

**An Optimal Acute Stroke Imaging Protocol: Our Perspective**

At the current moment, many institutions choose a combination of imaging techniques for the diagnosis, treatment selection, and monitoring of AIS patients. The choice varies dependent on patient factors (e.g., comorbidities, time from onset), as well as on institutional resources and expertise. Prior to the administration of IV thrombolytics, for example, only the possibility of hemorrhage needs to be ruled out; it is not necessary to wait for vascular imaging. In most hospitals, CT is still the imaging modality of choice; not only is it the fastest, most widely available technology, but it also has relatively few contraindications and is often more easily implemented than MRI. Indeed, an ideal stroke imaging technology should fulfill the following criteria: 1) it should be fast, 2) it should be easily implementable, 3) it should produce reliable results, 4) it should have very few contraindications, and 5) it should be safe. The additional information that can be gained from more advanced imaging techniques needs to be balanced against the time delays and postprocessing-related noise that come along with them (Figure 5).

At the current moment, CT seems to provide the most reasonable compromise/balance of these factors. Figure 6 outlines a current guideline-based imaging protocol. However, as our knowledge of stroke increases, along with broadening therapeutic options and indications, it is important to recognize the benefits of certain imaging technologies for specific situations. For the Canadian healthcare infrastructure and other countries with similarly wide-spread geographies, for example, the...
transfer of AIS patients from rural hospitals to EVT-capable hospitals often results in substantial time delays. While CTP is recommended for the late time window (>6 hours) by the current guidelines, in our experience mCTA is of at least equal value, requiring no post-processing and being both more robust and inclusive when selecting patients for treatment.

Importance of Acute Stroke Imaging Findings in the Post-Acute Phase

Neuroimaging is not only crucial for acute treatment decision-making; it can also be used to guide post-acute treatment and secondary stroke prevention in several ways.

Stroke Pattern

The patterns of ischemic lesions on MRI imaging can help to differentiate between large vessel or microvascular/embolic disease, which will result in different secondary stroke prevention regimens.

Pre-Existing Cerebrovascular Disease

MRI sequences such as gradient echo and susceptibility weighted imaging can elucidate etiologies of microbleeds and provide useful clues for diagnosis, such as cerebral amyloid angiopathy, which may lead to a more detailed diagnostic work-up and influence further management.

Extracranial Carotid Artery Disease

Extracranial MRA including vessel wall MRI and even routine CTA allow for plaque/vessel wall characterization for prognostication purposes, which can help in the investigation of stroke etiology (e.g., degree of carotid stenosis, carotid webs, symptomatic non-stenotic carotid disease [SyNC]) and guide
secondary prevention measures. Transcranial Doppler is a noninvasive, real-time assessment of cerebrovascular function without the need of contrast medium and can also provide information regarding vessel wall changes and carotid plaque morphology, certain features of which are associated with a higher risk of (recurrent) stroke.

New developments in the Pre-Hospital Setting

Despite the major strides made for the treatment of AIS in recent years, time still remains a limiting factor. Indeed, since 2015, many hospitals have had success in streamlining their workflows to shorten the time from admission to recanalization, thereby achieving higher rates of good functional outcome. However, the time from activation of emergency medical services to hospital admission will always remain variable and more complex to control. Nevertheless, imaging in the field could help first responders make critical decisions regarding transfer of a patient (e.g., to a primary stroke center versus a comprehensive stroke center with EVT capabilities). There are currently a number of technologies under development, including mobile stroke units (MSUs) and specially designed stroke helmets for the detection vessel occlusion and assessment of tissue perfusion. MSUs were first piloted in Germany in 2010 and are rapidly gaining attention. They are equipped with an on-board CT and are often accompanied by a stroke physician; patients can be screened for hemorrhage which would allow earlier IV thrombolysis administration, while some are outfitted with CTA capabilities, further aiding in patient triage. “Stroke helmets” employ electromagnetic, ultrasound, microwave, and EEG based technologies (among others) to differentiate between ischemic and hemorrhagic stroke, or other stroke mimics. Such technologies could help to substantially shorten the pre-hospital interval, thereby likely improving patient outcomes. Currently, however, most of these devices are in the early investigational phase.

Future Directions of Imaging

Finally, artificial intelligence and machine learning are rapidly changing the way image-based diagnosis and processing are performed. Recently, Wu et al developed a machine learning approach for the automatic segmentation of infarct lesions on NCCT images that had good agreement with stroke volumes as determined on DWI-MRI. As previously mentioned, another study demonstrated that mCTA-based automated prediction of ischemic brain tissue fate was feasible, with comparable results to CTP imaging. Deep convolutional networks have also been used to detect the presence of LVO on mCTA. Once fully developed and validated, these technologies will help to avoid misdiagnosis and delayed diagnosis of AIS, thereby reducing treatment delays, guiding patient triage and transfer, and ultimately improving patient outcomes, which is particularly valuable in the Canadian healthcare infrastructure with its wide-spread geography, in which the transfer of AIS patients from rural hospitals to EVT-capable hospitals is both time and resource-consuming and results in patients being treated far away from their homes and families.

Conclusion

Stroke imaging technology has advanced rapidly in recent years and will likely continue to do so. This is in part due to a need to adapt to novel treatment options, but also a result of the rise of artificial intelligence, machine learning, and automation. However, it is important to remember that outcomes are a result of a complex interaction of variables, from patient history to post-therapeutic rehabilitation strategies. While we may have a multitude of options at our disposal, imaging represents only one facet of the stroke story. Clinical presentation and imaging studies are complementary diagnostic measures we can continue to integrate and use to further improve our ability to offer this powerful treatment to as many patients as possible.

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