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Advances in Imaging of Neurovascular Emergencies on Computer Tomography CT

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Abstract

Purpose of Review This article aims to review some of the recent advances and utilization of different CT techniques in the assessment of major neurovascular emergences such as acute ischemic stroke, traumatic brain injuries, blunt cerebrovascular injuries, ruptured intracranial aneurysms, ruptured arteriovenous malformation, and cerebral venous thrombosis, which constitute a large number of patients presenting to the emergency room.

Recent Findings Many advanced imaging techniques have been developed in the past two decades aiming to improve the diagnosis of neurovascular emergencies, including CT angiography, CT perfusion, dual-energy CT, subtraction CTA, and imaging-related artificial intelligence.

Summary Reviewing and understanding the concepts and interpretation of new imaging techniques will help improve the diagnostic yield and provide prompt information vital for the triage and management of patients. Advanced, accurate, safe, and cost-effective imaging techniques are required to expedite the diagnosis and patient management process to achieve the best possible clinical outcomes.

Keywords Advanced imaging · Advanced neuroradiology · Neurovascular emergencies · Subtraction CT · CT perfusion · Artificial intelligence

Introduction

Neurological emergencies are the conditions affecting the brain, spinal cord, cranial and peripheral nerves. Acute onset neurological conditions are a major cause of patients visits to the emergency departments and a large percentage of these patients require one or more radiological examinations [1]. These neurological emergencies include but not limited to acute ischemic stroke (AIS), traumatic brain injuries (TBI), blunt cerebrovascular injuries (BCVI), ruptured intracranial aneurysms (rIA), intracranial hemorrhages related cerebral vascular malformation, and cerebral venous sinus thrombosis (CVT) [2–5•].

Imaging of neurovascular disorders has evolved tremendously in the past years including advances in non-contrast CT brain, CT angiography (CTA), CT perfusion (CTP), dual-energy CT, and subtraction CTA [2–5•]. Moreover, use of Magnetic resonance imaging is constantly increasing as problem-solving tools to answer a specific question about certain neurovascular disorders [2–5•]

In this review we will re-visit some of the advances and utilization of different CT techniques in assessing various neurovascular emergencies.

Acute Ischemic Stroke (AIS)

Stroke is the second leading cause of morbidity and mortality worldwidee [2]. There were around 13 million strokes in 2016 and approximately 87% of these patients had ischemic strokes [2]. Main role of neuroimaging in the setting of AIS is to identify intracranial hemorrhages, large vessel occlusions and tissue penumbra to triage patients appropriately for IV tPA and/or mechanical thrombectomy [1, 2, 6•].

Standard Imaging

Non-contrast CT head (NCCT) and CT angiogram (CTA) are standard imaging techniques for the evaluation of patient

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presenting to the emergency department with acute stroke symptoms [2, 6•]. NCCT is used to exclude intracranial hemorrhage and established large infarct core [6•, 7]. This has a vital role in confirming the eligibility of patients suitable for intravenous administration of tissue plasminogen activator (tPA) presenting within 6 h from symptoms onset and have a measurable neurological deficit [2, 6•]. The main role of CTA is to assess large vessel occlusion and patients selection for mechanical thrombectomy [7]. In addition, CTA source images provide additional information about parenchymal enhancement and are superior to define infarct core as compared to NCCT [8].

Advanced Imaging

CT perfusion (CTP) technique in AIS provides the physiological status of brain tissue perfusion and differentiates between infarcted tissue (core infarction) and viable tissue at risk (penumbra) [1]. CT perfusion techniques in the evaluation of patients presenting with acute ischemic strokes have been validated in many recent trials such as MR CLEAN-LATE, DAWN, and DEFUSE and all these trials have documented better patient outcomes with the use of CT perfusion for patient's selection for endovascular intervention [9–11].

CTP calculate different parameters that determine the core and penumbra, and these parameters include time to peak enhancement (T-max), mean transient time (MTT), cerebral blood flow (CBF), and cerebral blood volume (CBV) [1]. T-max reflects the time delay between the contrast bolus arriving in the proximal large vessel arterial circulation (arterial input function) and brain parenchyma after administration of intravenous contrast agent. MTT refers to the average amount of time for a volume of contrast to pass through a specific volume of brain tissue [1]. CBF refers to a specific volume of blood that passes through a specific volume of brain tissue in a given time unit [1]. CBV refers to the volume of flowing blood in a given volume of brain tissue [1]. Infarcted tissues have an increased T-max, MTT, decreased CBF and CBV, while brain tissues penumbra have an increased T-max, MTT, decreased CBF and normal or increased CBV [1] (Fig. 1).

Multiphase CTA is another technique used to assess patients collateral arterial flow in the territory of large vessel occlusion [6•, 12]. The multiphase CTA is performed by using iodinated contrast medium and the images are acquired in a time resolved manner in the peak arterial phase, peak venous phase and delayed venous phase [6•]. It has been shown that patients presenting with large vessel occlusion and good collateral arterial flow of the affected territory have good outcomes provided they have small core infarction [12]. However, this technique has been used in the ESCAPE trial and showed minimal benefits when compared to single phase CTA [6•]. Moreover, it has been shown that perfusion-based patient selection is superior to collateral flow-based patients' selection for post mechanical thrombectomy good outcomes [6•, 13].

Artificial intelligence is playing a major role nowadays in the assessment of acute stroke [14, 15]. There are many

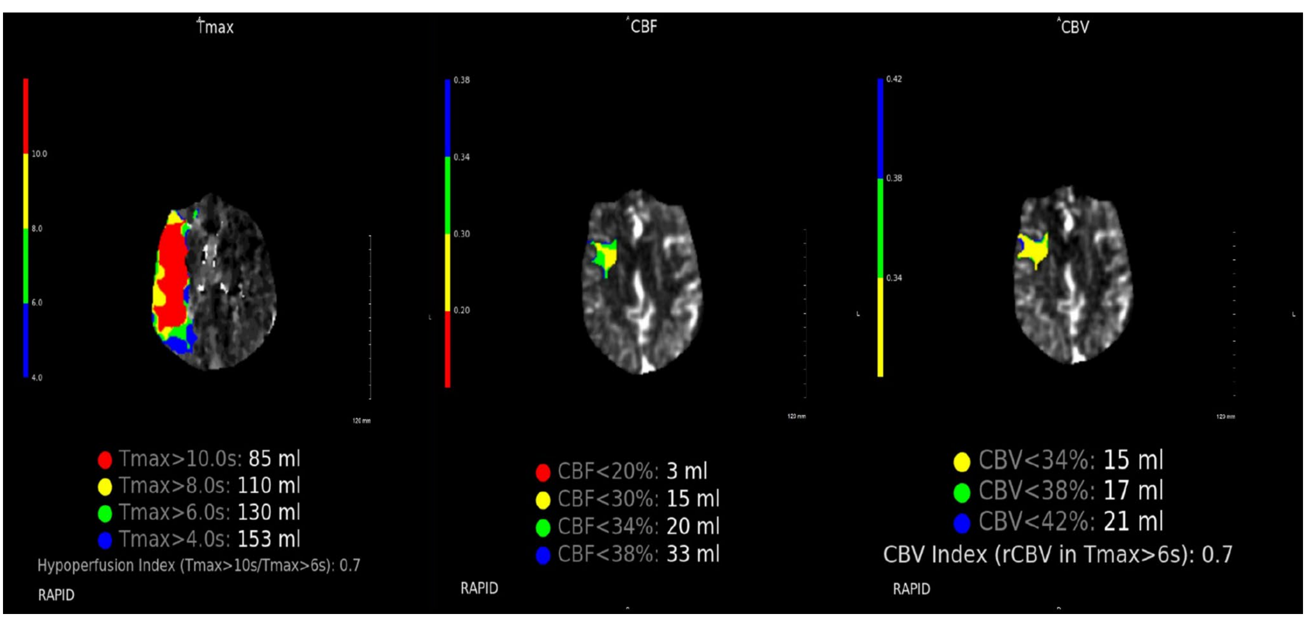

Fig. 1 Seventy-nine-year-old male patient presented with slurred speech, left upper and lower limbs weakness. Increased Tmax over the right MCA-territory compared to the left MCA-territory indicates the area at risk of infarction, A. Decreased CBF and CBV indicate the established infarcted tissue. Source: Personal-collection

different software that calculates and identify the core infarction, viable ischemic tissue, the site of large vessel occlusion and collateral vessels using different machine learning algorithms [14, 16]. One of the commonly used applications is RapidAI (iSchemaView, Menlo Park, California, USA) [16]. By using automated analysis, RAPID performs the measurements and segmentations to identify the core infarction and penumbra [16]. RAPID core infarction is identified as a region of brain tissue in one hemisphere with a relative CBF < 30% compared to the contralateral hemisphere, and penumbra with brain tissue volume having a Tmax > 6 s minus total volume of core infarct defined by CBF > 30% [16, 17] (Fig. 2).

Dual energy CT (DECT) is a promising advancement in neuroimaging that enhances the contrast resolution among different tissues [18, 19]. DECT enables neuroradiologists and neurointerventionalists to differentiate between iodine contrast and hemorrhage after mechanical thrombectomies [18]. DECT can show early areas of ischemia better than the routine single-energy NCCT brain, it also decreases the beam hardening artifacts and metallic artifacts from coils or surgical clips [19]. Basically, DECT is acquired by two different tube voltages, one low kilovoltage x-ray tube and one high kilovoltage X-ray tube simultaneously and then the two acquired sets of images are blended or undergo algorithmic materials decomposition [18, 19]. The results are 3 substances/views that can help in better tissue characterization, for example differentiating hemorrhage from iodinated contrast [18, 19] (Fig. 3).

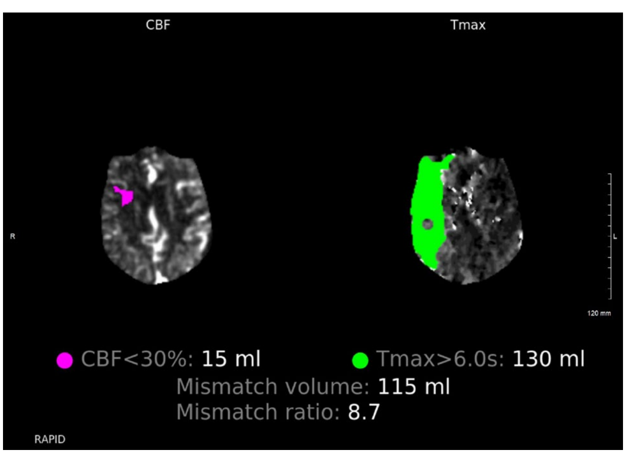

Fig. 2 The same patient in Fig. 1. The RapidAI shows the right temporal lobe core infarction (purple) as an area of decreased CBF of less than 30% compared to the same area in the left temporal lobe. The green area shows the area at risk of infarction which has a maximum residue function that takes more than 6.0 s. Source: Personal-collection (Color figure online)

Traumatic Brain Injury

Traumatic brain injury is one of the leading causes of morbidity and mortality and is defined as a damage to the brain caused by an external force [20, 21]. Either penetrating head injuries such as gunshots or knife wounds, or closed head injuries such as falls or motor vehicle accidents [20]. TBI is classified according to the Glasgow coma scale (GCS) into mild (GCS ≥ 13), moderate (GCS 9–12), and severe (GCS 3–8) [21].

Standard Imaging

According to the American College of Radiology Appropriateness Criteria, patients with moderate to severe closed head injuries (GCS < 13) should initially undergo NCCT of the brain to rule out intracranial hemorrhages [21]. The NCCT brain sometimes has limitations identifying brain contusions, diffuse axonal injuries (DAI), and signs of intracranial hypertension [21]. MRI brain with gradient echo (GRE), diffusion-weighted imaging (DWI), or fluid-attenuated inversion recovery sequences (FLAIR) can identify areas of microbleeds, DAIs, and intracranial hypertension even in mild TBI (GCS ≥ 13) [21, 22].

Advanced Imaging

Although MRI brain susceptibility-weighted imaging (SWI) sequence is beyond the scope of this review, this is an important advanced MRI technique that is more sensitive in detecting microbleeds in patients with TBI in the early and mild stages which can also predicts the cognitive outcomes on the long run [22].

Recently, CT perfusion has been used in patients with TBI to assess for viable brain tissue at risk (traumatic penumbra) and secondary TBI events that can happen hours to days after the injury [23•]. As mentioned above with regards to using CTP in AIS, different parameters MTT, CBV, and CBF are also used in TBI to assess the brain parenchyma [16, 23•]. The brain tissues viability is dependent on CBF, thus, alterations in CBF can disturb the electrical and metabolic neuronal activities [23•]. This process is managed by cerebral autoregulation which ensures adequate CBF to the brain tissues during these TBI alterations [16, 23•]. The sensitivity and specificity of CTP in TBI cases were 87.5% and 93.9%, respectively [23•].

The CTP findings in patients with cerebral contusions are seen in the cortical/subcortical regions with increased MTT, decreased CBV and CBF [23•]. In regions adjacent to an extra-axial traumatic hemorrhage or collection, the CBF would be decreased and improved after evacuating the

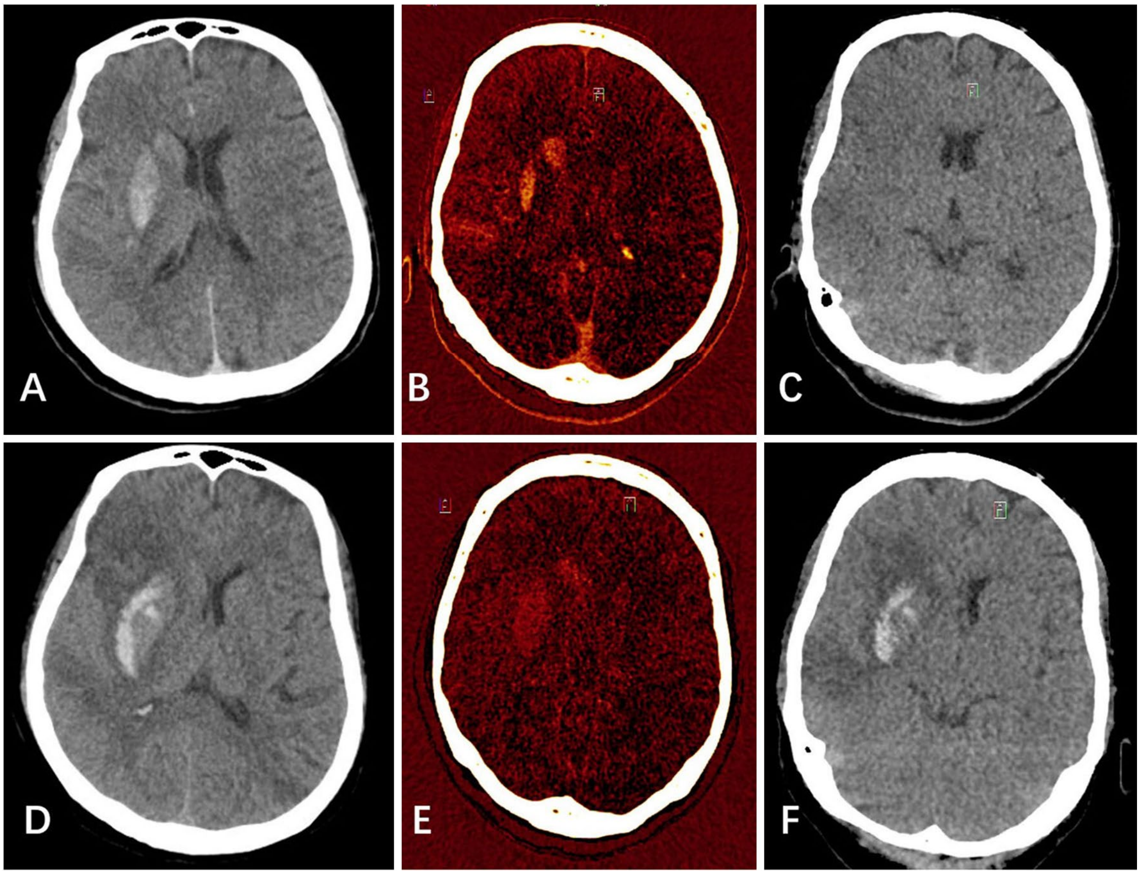

Fig. 3 Examples of hemorrhagic transformation and contrast extravasation with iodine overlay map (IOM), virtual non-contrast (VNC), and mixed images. **A**–**C** were mixed image, IOM, and VNC, respectively, from a patient's dual energy CT (DECT) immediately after endovascular thrombectomy (EVT). **A** showed hyperdensities in the right lentiform nucleus and caudate nucleus. In **B**, **C** combined, the hyperdensities were classified as pure iodine contrast. **D**–**F** were mixed image, IOM, and VNC, respectively, from the same patient's DECT 24 h after EVT. **D** also showed hyperdensities in the right lentiform nucleus and caudate nucleus. In **E**, **F** combined, the hyperdensities were classified as hemorrhage with iodine contrast. Adopted from Liu et al., 2020 [36],

hematoma/collection [23•]. In patients with post-TBI intracranial hypertension CTP showed increased MTT, decreased CBF and CBV [23•].

Blunt Cerebrovascular Injuries BCVI

BCVI is an umbrella term used to define blunt trauma to the extracranial, intracranial carotid arteries, and vertebral arteries [4, 24]. BCVI prevalence is 1–3% in blunt trauma population and up to 9% in patients with severe head injuries [4, 24]. The outcomes of BCVI depend largely on the grade of the injury starting from grade 1 luminal irregularities, dissections and up to higher grades of vascular occlusion and transection [4, 24]. The BCVI if left untreated can lead to brain infarctions and death [4, 24, 25]. It has been estimated that untreated cervical carotid injuries can lead to morbidity and mortality up to 67% and 38%, respectively, whereas untreated vertebral arteries BCVI can lead to morbidity and mortalities rates up to 24% and 18%, respectively [4]. There are screening guidelines during the initial trauma evaluation to identify patients who need further evaluation with radiological exams, which are beyond the scope of this article [4, 25].

Standard Imaging

The gold standard imaging technique in patients with BCVI is digital subtraction angiography (DSA) with highest sensitivity to detect BCVI and allows also the evaluation of collateral circulation [4, 24]. However, due to its invasive nature it is usually used in high-risk population and in patients with negative CTA scans but with persistent clinical suspicion of BCVI injury [4].

Advanced Imaging

Because of the higher cost and invasiveness of DSA, CTA has largely replaced DSA as a screening tool in patients suspected of BCVI [4]. In the past, CTA usage in BCVI patients was limited by the thick CT slices with low sensitivity and specificity identifying the injuries. However, recently with the availability of 32 channel and higher multidetector CT scanners, CTA sensitivity has reached up to 98% and specificity up to 100% [4, 24].

Ruptured Intracranial Aneurysms (rIA)

Subarachnoid hemorrhage (SAH) due to aneurysm rupture accounts for 85% of non-traumatic SAH [26, 27]. Patients presenting with symptoms related to SAH undergo NCCT of head to identify the site and amount of hemorrhage and to rule out the presence of hydrocephalus [28]. After confirming the presence of an intracranial aneurysms as the source of hemorrhage by CT angiogram, the treatment plans would include endovascular treatment with coiling with or without stenting or flow-diverters; or surgical clipping of the aneurysm [5•, 28]. Cerebral vasospasm is the main cause of mortality and morbidity in patients after successful treatment of ruptured intracranial aneurysms. Transcranial Doppler (TCD) is used as a screening tool to assess and monitor the prevalence of cerebral vasospasm [29•]. CT angiogram is used on a regular basis in high-risk patients for follow-up and to assess for vasospasm [28].

Standard Imaging

NCCT of the brain will be the first step to exclude the presence of an intracranial subarachnoid hemorrhage [26–28]. The site of the maximum bleeding and the higher blood density can sometimes suggest the site of the ruptured aneurysm; however, these are not always reliable findings [27, 28].

Most institutions perform CT angiogram as a second step to identify the cause of subarachnoid hemorrhage [28]. However, CT angiogram may have limitation and lower sensitivity for the detection of small aneurysms and vascular malformations. DSA is still considered gold standard imaging to identify small (less than 3 mm) aneurysm and high flow vascular malformations [28].

Advanced Imaging

The utilization of CTA to identify the presence of an intracranial aneurysm has been adopted by a large number of institutions due to its relatively safer and faster access than DSA [28]. The advances in modern multislice CT scanners have resulted in better sensitivity and specificity of aneurysm detection reaching up to 100% even in aneurysms smaller than 5 mm [30, 31]. 3D reformats images can be reconstructed after performing the CTA present more accurate morphological features of the aneurysm [28]. Better multiplanar reconstruction techniques have further facilitated detection of small aneurysms in difficult to assess areas.

Recently, ultra-high-resolution (UHR) CT scanners (Aquilion Precision, Canon Medical Systems, Otawara, Japan) have been developed and a new promising technique called subtraction CTA (sCTA) [5•]. Meijer et al. have used this technique in the follow up of patients with treated intracranial aneurysms either by endovascular means or surgical clipping and has shown comparable results to DSA [5•]. This technique basically uses a NCCT of the brain and subtracts it from the CTA in the postprocessing phase [5•]. UHR sCTA provides an in-plane spatial resolution of up to 0.234 mm which can show the fine details of the vascular structures [5•]. Using a metal artifacts reduction algorithm further increases the clarity and accurateness of the UHR sCTA by overcoming the metallic artifacts caused by the endovascular or surgical devices used to treat the aneurysm [5•] (Fig. 4, 5).

Moreover, CT perfusion can be used to assess the location and severity of cerebrovascular vasospasm and its related perfusion abnormalities [32]. It can identify severe vasospasm with risk of delayed ischemia and can thus guide the invasive treatment [32].

Arteriovenous Malformation AVM

AVM-related hemorrhagic events are considered one of the emergency conditions that patients present acutely with to the ER [33]. Different management approaches including conservative treatment, endovascular treatment, radiosurgery, open surgery or a combination of these approaches can be performed [33]. The standard imaging examination to diagnose AVMs are NCCT, CTA, MRA, and DSA which have been explained above [33]. AVMs are complex vascular pathologies that need thorough and detailed assessment of their angioarchitectures and flow hemodynamics which is typically achieved by using DSA [33]. CTA and MRA can determine the AVM location, nidus size, arterial feeders [33]. The flow hemodynamics and venous drainage are difficult to assess by standard CTA and MRA [33].

Advanced Imaging

The recent advances in multiphase CTA (time-resolved CTA or 4-dimention CTA) have shown promising results in identifying the critical key-imaging features of an AVM, which are important in the treatment planning and are almost

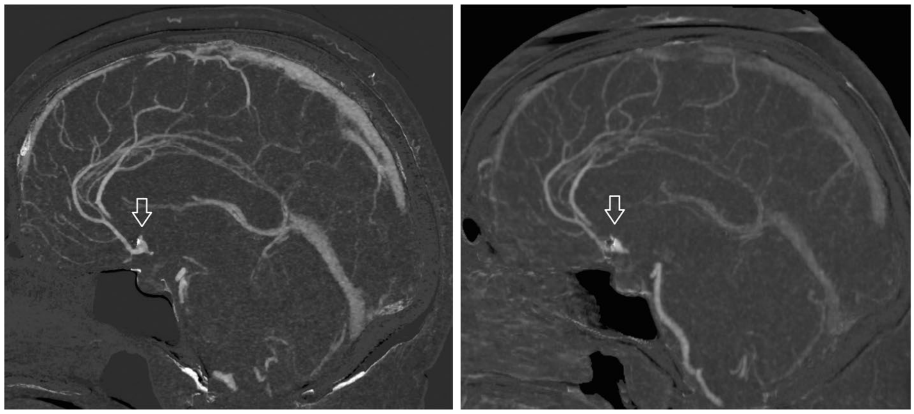

Fig. 4 Sixty-nine-year-old female with surgical clip-treated anterior communicating aneurysm. Follow-up with subtraction CTA demonstrates a remnant of the aneurysm (arrows). Image quality of subtraction CTA is superior on the UHR system (left image) as compared to subtraction CTA on a conventional CT system (right image) due to increased spatial resolution (0.25 × 0.25 mm versus 0.5 × 0.5 mm). Adopted from Meijer et al., 2019 [5•], CC BY

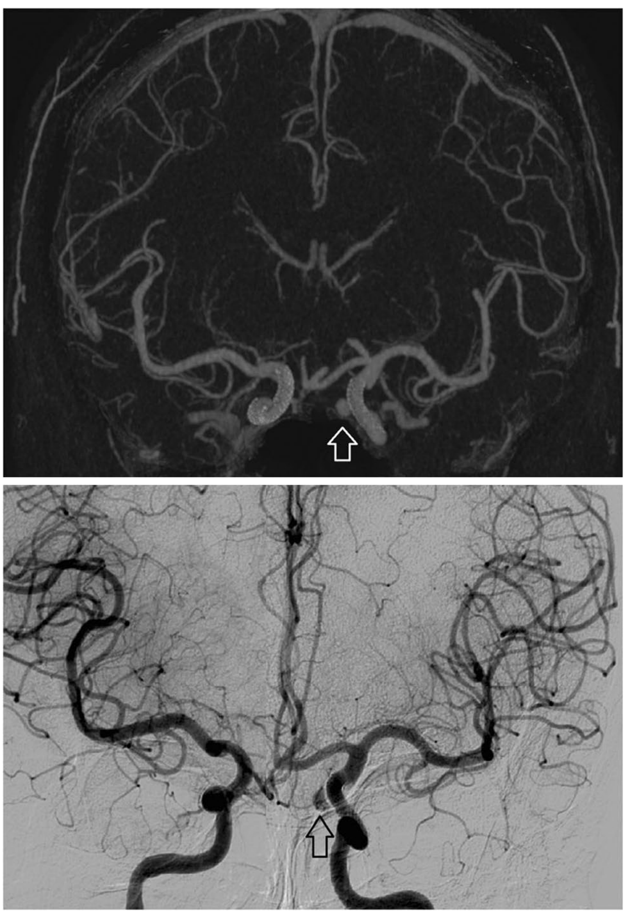

Fig. 5 Fifty-seven-year-old female with flow diverter placement for treatment of internal carotid artery (ICA) aneurysms on both sides. At follow-up, occlusion of the right ICA aneurysm and residual contrast filling of the left ICA aneurysm (arrows) was seen with full consistency between UHR subtraction CTA (top) and conventional angiography (bottom). Adopted from Meijer et al., 2019 [5•], CC BY

comparable to DSA. In addition, these noninvasive techniques provide better anatomical localization of the AVM, information about possible site of the rupture, venous drainage pattern, and secondary changes related to outflow obstruction [33].

Cerebral Venous Thrombosis (CVT)

CVT is defined as complete or partial thrombosis of a cerebral vein or a dural sinus. CVT accounts for up to 1% of all strokes and commonly patients present with headache or seizures [34]. The females are at increased risk of developing CVT especially at young ages. NCCT and CT venography of the head are usually the first radiological examinations to assess for CVT [34].

Standard Imaging

CT venography is usually the first radiological tool to diagnose CVT [35]. After performing a thin slices NCCT brain, approximately 100 ml of iodinated contrast is injected through a percutaneous venous canula [35]. Simultaneously CT venography is performed with standard CT parameters at a standard delay time of 30 s [35].

Advanced Imaging

In contrast to the standard CT venography, subtraction CT venogram (sCTV) scan be performed by digitally subtracting the thin slices NCCT from postcontrast scans to generate the 3D reconstructed images of the venous system [35]. A new protocol is described in the recent literature aiming to reduce both the amount of radiation exposure and the administered iodinated contrast, and to maximize the venous system enchantment for better visualization by using a time-density curve (TDC) [35]. TDC determines the time of peak enhancement of the intracranial venous system with the administration of a small dose of iodinated contrast [35]. The results of this technique showed better contrast attenuation of the intracranial main venous structures allowing for accurate assessment of small nonocclusive thrombi [35].

Conclusion

Neurovascular emergencies such as AIS, TBI, BCVI, rIA, AVM and CVT are among critical events that can affect the patient's short-term and long-term clinical outcomes. CT is the core modality for the evaluation of most neuro emergencies. The recent advancements in CT neuroimaging are providing prompt diagnosis and helping in optimal management of patients presenting in busy ER departments with acute neurological conditions. Understanding the new emerging imaging techniques will help to improve the patient's care and outcomes.

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Declarations

Conflict of interest The authors declare that they have no conflict of interests.

Ethical Approval This article does not contain any studies with human or animal subjects performed by any of the authors.

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