Introduction

Since its first introduction in 1971, computed tomography (CT) has evolved rapidly. With the evolution from fan beam to cone beam, and from axial to helical mode, the increase in the number of detectors (from a single detector array to 256/320 detector arrays), and the advent of dual energy technology, CT now offers very short scan time (even for extensive anatomical coverage), improved spatial and temporal resolution, and reduced patient dose, both in terms of radiation and contrast agent. CT is the imaging modality of choice in the emergency setting. It is fast, its requirements are low, and it is available 24 hours a day, 7 days a week. Modern CT scanners offer volumetric acquisitions, which improve the capability to evaluate intracranial and spinal structures in reconstructed three-dimensional (3D) views. With the development of post-processing software, CT has expanded its applications beyond the evaluation of structural anatomy to include functional analyses such as perfusion-CT (PCT) to assess cerebral blood supply (Table 1.1).

Despite these technological advances, the basic imaging principle of CT has not been changed and relies on X-ray physics. The radiation dose concerns associated with CT remains, although it has been alleviated by a number of dose-reduction techniques implemented by the imaging manufacturers. Nowadays, the radiation dose of a non-contrast head computed tomography (NCT) ranges from 1.7 to 2.5 mSv [1,2], lower than the background radiation for a person living in Boston for a year (approximately 3 mSv) [3]. The estimated lifetime risk of death from cancer that is attributable to a single NCT is 0.01–0.02% [4]. With the advent of dual-energy CT, the radiation dose associated with CT may be reduced further when contrast-enhanced examination is applied [5].

Computed tomography technology

CT is an imaging technique based on X-rays, a form of electromagnetic radiation with a wavelength range of 0.01–10 nm. X-ray beams can traverse the human body and be used to create an image (they can penetrate, but do no harm), while at the same time the photon energy it carries makes it an ionizing radiation, which can cause harm to living tissue (in proportion to the absorption). CT imaging uses a specific range of wavelengths of X-rays (wavelength below 0.2–0.1 nm) to obtain good penetration and limit the ionizing radiation harm. Unlike conventional X-ray imaging, CT images are not developed directly from the attenuation of projection X-rays. Instead, slices of specific areas of the body are imaged and divided into a matrix of voxels, the intensity of which is calculated from multiple projections from an X-ray source to a panel of detectors, both rotating in the CT gantry. The attenuation value of an individual voxel depends upon its contents and can be quantitatively scored in Hu (Hu; called after the inventor of CT), which ranges from −1000 Hu to +1000 Hu, with water in the middle (Hu = 0), and air (−1000 Hu) and bone (+1000 Hu) at the extremities of the scale. Modern CT scanners can reconstruct axial, sagittal, coronal, oblique, 3D, or even 4-dimensional (4D) images.

Single-slice versus multislice computed tomography scanners

In very early single-slice CT scanners, a single row of detectors were arrayed in a line opposite to the X-ray tube inside the CT gantry. These scanners used a narrow beam of X-rays (pencil width), which was collimated and developed very little scatter when it passed through the human body. With such scanners, one gantry rotation could only sample one slice.

In multislice CT scanners, detectors are arrayed linearly in multiple rows, so that the machine can cover multiple slices in one rotation (up to 320 slices with the most advanced CT technology). Also, a fan beam X-ray is used. The benefits of this geometry are not only limited to obtaining a larger coverage with one single rotation, but can also shorten the scanning time. With multislice CT scanners, the spatial and temporal resolution, and the contrast resolution are also greatly improved.

The latest generation of CT scanners (e.g. 320-detector row CT) uses a cone beam of X-rays with a flat panel detector for capturing the images. Cone-beam CT scanners can produce 3D images with a single rotation of the gantry [6], and also time-resolved CT-angiogram (4D CTA) showing the dynamic progression of the contrast through arteries and veins [7].

Image reconstruction algorithms

For a considerable time, filtered back-projection has dominated the field of CT image reconstruction. Filtered back-projection runs
the projection images back through the image to obtain a rough approximation of the original object (back-projection), and uses a high-pass filter to eliminate the image blurring caused by such ‘back-projection’.

More recently, iterative reconstruction algorithms have been developed, originally to reduce the noise of images. These algorithms consist of a series of sequential reconstructions and corrections—forward- and back-projection reconstruction steps, and comparison of the projection data with the real measured raw data and correction of deviation in projection between each step. The correction is based on the statistical counting of the detected photons in the reconstruction process. The iterative process can be performed in the raw data domain, in the image domain alone, or in both [8,9]. Iterative reconstruction can reduce the radiation dose associated with CT studies by 20–40% without compromising image quality [10–13]. One of the downsides of iterative reconstruction lies in the longer image reconstruction time.

### Single-source versus dual-source computed tomography

Dual-energy CT is an emerging CT modality. There are currently two ways used for dual-energy scanning:

1. Two X-ray tubes and two detectors (mounted on a CT gantry with a mechanical offset of 90°) with the two X-ray tubes being operated at different voltages.
2. A single X-ray tube that can rapidly switch its peak voltage and one detector.

Through the simultaneous acquisition of two image series with different kVp (e.g. 40 and 140 kVp), dual-energy CT facilitates material separation. For example, it can be used to generate virtual non-contrast images of the brain from a contrast-enhanced CT; this also allows the removal of bone and calcium from a CTA [14,15].

### Computed tomography imaging modalities

#### NCT
Routine NCT is performed in the axial plane, parallel to the orbitomeatal line, with 2.5-mm thick slices. For cervical spine imaging, 0.625-mm thick slices are obtained, while 1.5-mm thick slices are the standard for imaging the thoracic and lumbar spine.

NCT is used for the initial evaluation of many intracranial and spinal lesions, especially in the acute setting. NCT is the first-line examination for acute traumatic brain injury (TBI) and stroke, since it is especially suited for detecting ischaemia, haemorrhage, and skull fracture.

NCT is less sensitive than magnetic resonance imaging (MRI) for the assessment of posterior fossa and brainstem lesions, due to hard-beam artefacts (Fig. 1.1), and for the diagnosis of conditions such as haemorrhagic or non-haemorrhagic diffuse axonal injury, contusion, early infarction, encephalitis, and brain tumour.

#### Contrast-enhanced computed tomography
Enhancement after injection of iodinated contrast indicates intravascular enhancement due to an increased permeability of the blood–brain barrier, which leads to a leakage of the contrast material into the interstitium. By analysing the enhancement patterns associated with contrast agent injection, contrast-enhanced computed tomography (CECT) can help differentiate lesions such as vascular malformations, neoplasms, and active inflammation (infectious and non-infectious) [16].

#### Computed tomography angiography
Computed tomography angiography (CTA) with multiplanar reformatted images, maximum intensity projection images (MIP), and 3D reconstructions of axial source images provide images comparable with, or even superior to, those obtained with digital subtraction angiography (DSA) [17,18]. Unlike time-of-flight magnetic resonance angiography (MRA), CTA is less susceptible to turbulent or slow-flow artefacts. Spatial resolution of CTA is approximately twice that of gadolinium-enhanced MRA [19]. CTA has become
the modality of choice to non-invasively assess cervical and intracranial vessels. Dynamic CTA provides dynamic, real-time information, similar to that offered by DSA, which is rarely used for diagnostic purposes.

**PCT**

PCT evaluates capillary, tissue-level circulation, which is beyond the resolution of traditional anatomic imaging. PCT is most commonly carried out using dynamic sequential scanning of a pre-selected slab of the brain (modern CT scanners offer whole-brain coverage), during the injection of a bolus of iodinated contrast material as it travels through the vasculature. By recording the wash-in and wash-out of the contrast bolus through the cerebral vasculature, several parameters describing the cerebral perfusion, i.e. cerebral blood flow (CBF), cerebral blood volume (CBV), mean transit time (MTT), time to peak (TTP), and blood-brain barrier permeability (BBBP), can be quantitatively evaluated on reconstructed colour maps.

PCT limitations and pitfalls include the following:

1. Complex post-processing and long-lasting experience in interpretation of the images.
2. Due to arterial input function (AIF) delay, vascular stenosis may result in an overestimation of the area of cerebral perfusion abnormality [20]. It is therefore of importance that PCT should be performed and interpreted with concurrent CTA.
3. Although higher than MR perfusion-weighted imaging [21] and SPECT/PET, the resolution of PCT maps is still relatively low. Small infarcts may be missed, and white matter changes can be misdiagnosed.

**Common CT features**

CT findings are categorized into hyperdense, isodense, and hypodense, depending on their density compared with that of normal brain tissue (approximately 40 Hu). Normal cerebrospinal fluid (CSF) has a density of around 5 Hu. Bone density is greater than 350 Hu, fat density is –100 Hu, and that of air is –1,000 Hu.

**CT hyperdensity**

**Acute intracranial haemorrhages**

Acute haemorrhage always appears as a hyperdense area in any region of the brain parenchyma, ventricles, subarachnoid space, or extra-axial space. Over time, intracranial haemorrhages become isodense (in the subacute phase) [23] and hypodense (in the chronic phase) [24]. Of note, low attenuation within an acute hematoma may indicate hyperacute, ongoing bleeding [25].

**Vascular clot**

An acute thrombus can be detected on NCT as an area of hyperdensity, featuring the ‘dense artery sign’ in the setting of a M1 occlusion of the middle cerebral artery (MCA) (Fig. 1.2), and the ‘dot sign’ in the setting of a M2 or M3 occlusion. Venous sinus thrombosis also appears hyperdense on NCT, while featuring a delta sign or triangular lack of contrast filling on post-contrast CT.

**Calcifications**

Calcifications are very hyperdense. Some calcifications in the brain are within normal limits, e.g. pineal gland calcifications, choroid plexus calcifications, falx calcifications, and basal ganglia calcifications/mineralization. Basal ganglia calcifications (and cerebellar dentate nuclei calcifications) are particularly pronounced in patients with Fahr’s disease [26]. Calcifications are also seen in a variety of pathological conditions, e.g. vascular malformations, chronic haematomas, brain infections, brain tumours, and congenital malformations, such as Sturge–Weber syndrome and tuberous sclerosis.

**Others**

Highly cellular neoplasms, such as lymphomas, can appear as hyperdense.

**CT hypodensity**

**Oedema**

Subacute infarcts, infections, and brain tumours alter the permeability of the blood–brain barrier, resulting in vascular leakiness and water extravasation into the interstitial space, or vasogenic oedema. The accumulation of interstitial water decreases the attenuation of brain tissue and features a hypodensity. Likewise, chronic ischaemia causes encephalomalacia and gliosis, which also present as hypodensity on CT.

**Hydrocephalus**

Hydrocephalus relates to enlarged ventricles. In obstructive hydrocephalus, ventricles upstream of an obstructive lesion are selectively dilated (Fig. 1.3). In communicating hydrocephalus, all ventricles are dilated.

**Mass effect**

Mass effect refers to the deviation or distortion of normal structures by an abnormal structure or mass, and the swelling accompanying it. Mass effect is typically observed in the case of large intracranial haematomas and brain tumours, as well as in the setting of malignant infarct. Early mass effect is seen as local effacement of sulci. Progressive mass effect results in midline shift, ventricular entrapment, and herniation (Fig. 1.4). Ventricular entrapment typically occurs when there is significant midline shift, the foramen of Monroe is compressed, and the drainage of the lateral ventricles is impaired. There are different types of herniation—subfalcine, uncal, downward transentorial, upward transentorial, and tonsillar and transtentorial herniation types. Severe herniation can cause
secondary ischaemic lesions, by compression of neighbouring arteries (anterior cerebral artery by subfalcine herniation, posterior cerebral artery by uncal and downward transtentorial herniation), and is lethal without prompt surgical decompression.

**CT clinical applications**

**Ischaemic stroke**

NCT is the imaging modality of choice to initially assess patients suspected of acute stroke, despite its limited sensitivity to ischaemia in the first few hours following symptom onset [27]. Sensitivity to acute ischaemia can be improved by setting the window centre level around 30 Hu and narrowing the window width to 8–10 Hu [28]. The role of NCT in the setting of an acute stroke is mainly to rule out the presence of haemorrhage [29] and mimics of stroke, such as infection, inflammation, and neoplasm. Early signs of ischaemic stroke on NCT include sulcal effacement, blurring of cortical gray–white matter differentiation, and in 50% of patients [30] a dense artery sign, as described previously. The Alberta Stroke Program Early CT Score (ASPECTS) quantifies the extent of the ischaemic changes visible on CT and helps to determine whether

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**Fig. 1.2** Hyperdense MCA sign caused by an acute intravascular clot. This finding on non-contrast CT (a, arrow) corresponds to a segmental filling defect on CT-angiography (b,c, arrows) and on digital subtraction angiography (d, arrow).

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**Fig. 1.3** Obstructive hydrocephalus caused by colloid cyst in the foramen of Monroe (arrow). The obstruction led to sequential enlargement of bilateral ventricles (a, arrowhead) and interstitial oedema in periventricular tissues (b, star).
an acute stroke involves more than one-third of the MCA territory. The latter represents a contraindication to the administration of IV tissue plasminogen activator (tPA), together with the presence of haemorrhage on the admission NCT [29]. In the subacute phase of an ischaemic stroke, a typical ‘wedge-shaped’ hypodensity can be seen on NCT (Fig. 1.5).

CTA is routinely used to detect the exact site of arterial occlusion in stroke patients. Compared with DSA, CTA has a 98.4% sensitivity and 98.1% specificity for detecting proximal intracranial arterial occlusion [23], and an 85% sensitivity and 93% specificity in detecting significant extracranial arterial stenosis [30]. In addition to the luminal evaluation, CTA is capable of evaluating the arterial wall, detecting vasculopathies (for instance, dissection), and characterising carotid atherosclerotic plaques [31]. Intracranially, CTA source images have increased sensitivity for acute ischaemic changes and can assess the collateral circulation distal to an arterial occlusion. Finally, when the stroke CTA scan extends below the origin of the aortic arch to include the left atrium or the whole heart, CTA can detect the presence of a left atrial or ventricular thrombus.

PCT is increasingly recognized as a diagnostic tool in patients with suspected stroke. Its applications in the setting of stroke include, but are not limited to:

1. Improving the sensitivity and accuracy of stroke diagnosis (in some cases, a lesion on PCT leads to more careful scrutiny and identification of a vascular occlusion that was not evident (Fig. 1.5), particularly in the M2 and more distal MCA branches) [32–35].

2. Excluding stroke mimics [36].

3. Better assessment of the ischaemic core [34] and collateral flow [18].

4. Prediction of haemorrhagic transformation and malignant oedema [37, 38].

Currently, different PCT software use different methods to process the data, and extract the infarct core and penumbra information. Standardization of PCT processing and interpretation is lacking. The use of a relative MTT threshold of 145% of the contralateral values to delineate the total ischaemic area is suggested, and an absolute CBV threshold of 2 mL/100 g to differentiate the infarct core and the penumbra within the total ischaemic area [39].

The safety of the combined use of CTA and PCT in stroke patients has been well documented [40]. Iodinated contrast administration for CTA/PCT does not cause significant renal injury nor does it interfere with the safety and efficacy of the tPA treatment [41].

Intracranial haemorrhage
The AHA/ASA guidelines indicate that either NCT or MRI may be used in the initial diagnostic evaluation of an intracranial haemorrhage (ICH) [42].

The majority of spontaneous ICHs are related to arterial hypertension. Hypertensive ICHs (Fig. 1.6) tend to involve the basal ganglia, thalamus, cerebellum, and brainstem, resulting from the rupture of micro-aneurysms of perforating vessels in these regions. When multiple haematomas are seen, if the haematomas have an irregular shape, or if they occur in unusual locations, secondary ICH should be considered.

Subarachnoid haemorrhage (SAH) occurs in the setting of trauma and of aneurysmal rupture (Fig. 1.7). Sensitivity of NCT to SAH in the first 24 hours is close to 100%. After 48 hours NCT sensitivity decreases to less than 85% [43]. In the presence of a negative NCT after 48 hours, a lumbar puncture is then required to detect xanthochromia.

CTA is used in patients with acute ICH for the purpose of identifying secondary causes of ICH [44]. CTA has a sensitivity and specificity comparable with DSA in terms of detecting intracranial aneurysms [45, 46]. CTA presents a number of advantages in terms of surgical planning—CTA data can easily be uploaded to neuro-navigation systems [47], and show precisely the relationship of the aneurysm to the skull base [48, 49], calvarium, and adjacent veins [50]. CTA is also useful in planning an endovascular intervention.

CTA and CECT can detect the ‘spot sign’, corresponding to the acute extravasation of contrast in the haematoma (Fig. 1.6). A ‘spot sign’ is indicative of haematoma expansion [51] and predictive of a poor outcome.

PCT has been used to detect a ‘penumbra’ surrounding haematomas. The existence of such a penumbra surrounding haematomas is still very much debated [52, 53]. In a series of patients who underwent surgical haematoma evacuation, PCT after surgery demonstrated a correction of the perfusion deficit surrounding the haematoma, suggesting that the latter represents reduced oxygen demand of tissue damaged by pressure and clot components [52].
Fig. 1.5 Typical CT imaging workup in a patient suspected of acute ischaemic stroke. (a) NCT shows mild effacement of the right lentiform nucleus. (b) PCT shows the right MCA to be ischaemic, with a mixture of ischaemic core (red) and penumbra (green). (c) CT-angiography demonstrates the right MCA occlusion (arrow) responsible for the ischaemia, later confirmed on digital subtraction angiography (d, arrow). (e,f) Follow-up NCT and PCT demonstrate that, in the absence of early recanalization, the whole ischaemic territory infarcted.

Fig. 1.6 'Spot sign' on contrast-enhanced CT. (a) NCT shows an intraparenchymal haematoma in the left thalamus with extension in the third ventricle. (b) Contrast-enhanced CT shows a ‘spot sign’ (arrow) within the parenchymal haematoma, indicating active extravasation of contrast. (c) The size of the parenchymal haematoma and the intraventricular extension have progressed significantly, as typically seen when the ‘spot sign’ is present.
PCT is also used to detect vasospasm, one of the complications of subarachnoid haemorrhage that typically occurs 4–7 days following SAH, and it adds prognostic information regarding delayed cerebral ischaemia and poor outcome [54,55].

Another complication of SAH is communicating hydrocephalus, which can be diagnosed early on NCT.

**Traumatic brain injury**

CT is the imaging modality used to screen trauma patients in the acute phase [56]. Head NCT is indicated in trauma patients with loss of consciousness or post-traumatic amnesia if one or more of the following is present—age greater than 60 years, headache, vomiting, drug or alcohol intoxication, deficits in short-term memory, physical evidence of trauma above the clavicle, Glasgow Coma Scale score less than 15, post-traumatic seizure, focal neurological deficit, or coagulopathy [57].

Skull fractures may be linear, comminuted, or depressed (Fig. 1.8). They are demonstrated as discontinuities with or without displacement on the CT bone windows, and may be associated with extra-intracranial air and/or haemorrhage. Whenever a bone fracture is identified, underlying brain parenchyma should be scrutinized for traumatic injury. Thin-slice CT with multiplanar reformats increases the sensitivity of the technique to subtle skull fractures, e.g. of the temporal bone.

Epidural haematomas (EDHs) are associated with skull fractures, and generally result from a traumatic injury to branches of the middle meningeal artery. An EDH appears on NCT as a lenticular or biconvex blood collection. EDHs can cross dural insertions (falx, tentorium), but do not usually cross suture lines.

Subdural haematomas (SDHs) occur in elderly patients with brain atrophy. They usually occur in the absence of skull fractures. They have a crescentic shape on NCT. SDHs can cross sutures. They do not cross, but extend along dural attachments (falx, tentorium). Acute and subacute SDHs may be subtle and difficult to detect. An appropriate, narrow CT window when reviewing NCT can help, together with a subtle loss of normal brain sulci or the buckling of gray–white matter junction caused by the SDH.

Traumatic SAH is usually more localized than aneurysmal SAH, and generally has its epicentre at the site of the coup. As a result of contrecoup injury, traumatic SAH may also occur contralateral to the side of direct impact [25].
Parenchymal contusions on NCT appear as focal low-density areas, except if they are haemorrhagic, in which case they appear as hyperdense. Contusions can be seen deep to a skull fracture or on the opposite side of the brain, as part of a contrecoup injury.

The above CT features of TBI constitute the core of the Rotterdam CT classification (Table 1.2).

Penetrating injuries can damage cervical and intracranial arteries and veins. Skull fractures, especially skull base fractures, can also result in vascular injuries. The latter can be evaluated by CTA (or CT-venogram). CTA can detect traumatic dissection and pseudoaneurysms with high sensitivity.

PCT abnormalities have been reported after TBI. Focal perfusion abnormalities are observed in and around contusions [59], and can be detected before structural abnormalities become apparent. PCT abnormalities might be useful to triage patients with extra-axial blood collections who need aggressive surgical treatment versus those who can be treated conservatively [60]. In TBI patients, baseline PCT hyperaemia is associated to a favourable outcome, while oligaemia is the hallmark of an unfavourable outcome [61]. PCT can provide information about cerebral vascular auto-regulation [60], and therefore can be used as a monitoring tool in TBI patients.

Modern CT with multiplanar reformats is the gold standard for the evaluation of the cervical spine for fractures, and has a sensitivity that is two or three times that of plain films [62]. Also, CT is more accurate than plain films in diagnosing thoracolumbar spine traumatic injuries (Fig. 1.9) [63]. CT can provide indirect signs to suggest ligamentous injury, but when these are suspected MRI is the preferred method of evaluation.

### Table 1.2 Rotterdam Classification score

<table>
<thead>
<tr>
<th>Predictor value</th>
<th>Score</th>
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<tbody>
<tr>
<td>Basal cisterns</td>
<td></td>
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<tr>
<td>Normal</td>
<td>0</td>
</tr>
<tr>
<td>Compressed</td>
<td>1</td>
</tr>
<tr>
<td>Absent</td>
<td>2</td>
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<tr>
<td>Midline shift</td>
<td></td>
</tr>
<tr>
<td>No shift or shift &lt;5 mm</td>
<td>0</td>
</tr>
<tr>
<td>Shift &gt;5 mm</td>
<td>1</td>
</tr>
<tr>
<td>Epidural mass lesion</td>
<td></td>
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<tr>
<td>Present</td>
<td>0</td>
</tr>
<tr>
<td>Absent</td>
<td>1</td>
</tr>
<tr>
<td>Intraventricular blood or traumatic SAH</td>
<td></td>
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<tr>
<td>Absent</td>
<td>0</td>
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<tr>
<td>Present</td>
<td>1</td>
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Note: to make the grading numerically consistent with the grading of the motor score of GCS and with Marshall CT classification, the final score is the sum of the scoring items +1.


Fig. 1.9 Spine fractures. (a) Lateral plain film and (b) anteroposterior myelogram demonstrate two compression fractures (L1 and L4, arrows) in a severely osteoporotic spine. (c,d,e) CT and (f) MRI allow better characterization of the posterior wall and any compromise of the spinal canal by fracture fragments (arrowheads).

### Others

MRI, and not CT, is the standard-of-care for the evaluation of patients with suspected epilepsy, infections, or brain tumours. CT in these patients is only obtained to rule out haemorrhage, hydrocephalus, or mass effect, especially in the emergency setting. CT is usually obtained with contrast in these cases.
Conclusions

CT is the fastest neuroimaging modality and has been established as the first line of examination in the setting of stroke and TBI. With its exquisite spatial resolution and functional capabilities, coupled with new developments, such as whole-brain coverage and dual-energy scanning, CT will remain the test of first choice in the evaluation of neurological disorders in the emergency setting.

References