REVIEW ARTICLE

Neuroimaging in adult penetrating brain injury: a guide for radiographers

Nikki Temple, BSc (ExSci), MPHAdv, MDR,[1] Cortny Donald, BSc Biotech Adv (Hons), MDR,[1] Amanda Skora, BSc (Hons), MDR,[1] & Warren Reed, BSc (Hons), Post Grad Cert (T&L), PhD[2]

[1]Discipline of Medical Radiation Sciences, The University of Sydney, Lidcombe, New South Wales, Australia
[2]Medical Image Optimisation and Perception Group, Discipline of Medical Radiation Sciences, The University of Sydney, Lidcombe, New South Wales, Australia

Abstract

Penetrating brain injuries (PBI) are a medical emergency, often resulting in complex damage and high mortality rates. Neuroimaging is essential to evaluate the location and extent of injuries, and to manage them accordingly. Currently, a myriad of imaging modalities are included in the diagnostic workup for adult PBI, including skull radiography, computed tomography (CT), magnetic resonance imaging (MRI) and angiography, with each modality providing their own particular benefits. This literature review explores the current modalities available for investigating PBI and aims to assist in decision making for the appropriate use of diagnostic imaging when presented with an adult PBI. Based on the current literature, the authors have developed an imaging pathway for adult penetrating brain injury that functions as both a learning tool and reference guide for radiographers and other health professionals. Currently, CT is recommended as the imaging modality of choice for the initial assessment of PBI patients, while MRI is important in the sub-acute setting where it aids prognosis prediction and rehabilitation planning, Additional follow-up imaging, such as angiography, should be dependent upon clinical findings.

Penetrating brain injury (PBI) includes any traumatic injury where an object pierces the skull and breaches the meninges surrounding the brain. PBIs are less prevalent than blunt head injuries, representing ~0.4% of injuries, however, they often have more complex damage, worse prognosis and higher rates of morbidity and mortality.[1,2] Bullets are the most common foreign bodies in PBI,[3] however, chopsticks,[4] toothbrushes,[5] nails[6] and knives[7] have also been reported. Foreign bodies into the cranium pose immediate complications, such as pneumocephalus, intracerebral haemorrhage, contusions and brain stem injury, which, in the short to medium term sequelae, can lead to abscesses, meningitis and encephalitis.[4] It is stated that advanced age, a Glasgow Coma Scale (GCS) of 3, bilaterally dilated pupils and high intracranial pressure are associated with worse outcomes.[8]

PBI management differs greatly from that of non-penetrating brain injury due to the mechanism of injury and subsequent pathophysiology of the trauma.[8] Initial management involves surveying and stabilising the patient to reduce the risk of secondary brain damage, resulting from increased intracranial pressure or reduced cerebral perfusion.[8] Subsequent to this survey, a decision is made as to whether neuroimaging is required. Comprehensive review articles have been written on the management for PBI,[8,9] however, no guidelines appear to have been reported in the literature suggesting imaging pathways for adult PBI. This article aims to review the clinical indications for the use of the different imaging modalities used in the assessment of PBIs and to develop an easy to navigate imaging pathway that radiographers and other relevant health professionals can refer to when presented with an adult patient with PBI.

It is important to note that there are two distinct types of damage that can result from a PBI, namely primary brain injury and secondary brain injury. Primary brain injury refers to injury caused by the trauma of the penetrating object itself. The effects are generally less devastating than secondary brain injuries and include haemorrhage, intracranial lesions and skull fractures. Primary axonal damage can trigger events that can lead to secondary brain injury, such as neurotoxic biochemical cascades, haemotoma formation, blood loss, infection or seizure.[10] These effects usually occur around 24–48 h post-initial injury and are generally more devastating, resulting in brain herniation infarction and/or post-traumatic atrophy. Primary and secondary brain injuries are detectable at different times, using different imaging modalities, therefore, there are two goals in PBI imaging. The first is to assess primary brain injury in the acute setting to aid management and treatment planning, and secondly to detect secondary brain injury in the sub-acute setting which helps predict long-term effects and patient prognosis.

Indications for Imaging

Neuroimaging provides valuable information concerning the entry and exit sites of penetrating objects, vascular injury and is vital for planning surgical intervention.[8] Traumatic brain injuries are commonly classified using the GCS, which grades a patient based upon eye, verbal and motor function.[11] Brain injuries are classified into mild (GCS 13–15), moderate (GCS 9–12) and severe (GCS 3–8).[12,14] The Canadian CT Head Rules (CCHR) are a set of guidelines that may be used in deciding whether head computed tomography (CT) is required in patients with traumatic brain injury.[13] These rules are a set of highly sensitive (100%) and moderately specific (50%) risk factors that, if present, warrant CT imaging of the head. The high-risk factors include: GCS score <15 two hours post- injury, suspected open or depressed skull fracture, more than two episodes of vomiting, physical evidence of basal skull fracture and age greater than 65. The two medium-risk factors are: amnesia of events that happened more than 30 min before injury and a dangerous mechanism of injury (MVA, fall >3 feet or 5 stairs). It was concluded that patients with any one of the high-risk factors are at substantial risk for requiring neurosurgery, and CT should be mandatory in these patients.[13] In addition to the high-risk factors identified in the CCHR, the National Institute for Clinical Excellence (NICE) guidelines recommend urgent imaging for all patients with GCS less than 13 on initial assessment or GCS less than 15 two hours post-injury, as well as any patient with a focal neurological deficit,

post-traumatic seizure or coagulopathy.[12,14] However, CT is not the only modality indicated for neuroimaging in PBI – magnetic resonance imaging (MRI), angiography and in some cases plain radiographs are also useful. Table 1 summarises the main modalities used in PBI imaging, including the clinical indications and contraindications for each modality, which will be discussed in depth later in this review.

Role of Plain Radiography

Traditionally, imaging of the cranium relied on skull radiographs.[15] Before CT and MRI, plain skull radiography was performed to localise wound sites or penetrating objects, and predict intracranial injury, however, plain radiography is not optimal at detecting foreign bodies (e.g. wooden objects), and has low sensitivity compared to CT in detecting skull fractures or a change in intracranial pressure.[16,17] Plain films can still

Table 1 Summary of clinical indications and contraindications for imaging modalities used in penetrating brain injury.

Imaging modality	Clinical indications	Contraindications
Skull radiographs	Not recommended (unless CT unavailable)	
Computed tomography	Acute penetrating brain injury Meets NICE guideline Metal foreign body	Wooden foreign body
DECT	Large metallic foreign body	
Magnetic resonance	Organic foreign body	Metal foreign body Unstable patient
DWI	Suspected DAI	
t-PEPSI	Un-cooperative, unstable patient	
SWI	Suspected micro-haemorrhage/DAI	
SS-EPI	Un-cooperative, unstable patient	
Cerebral angiography	Risk of vascular injury	Severe iodinated contrast allergy
Conventional	Intervention required	
CTA	Unstable patient	
MRA	Stable patient, younger patients	

SS-EPI, single-shot echo-planar imaging; NICE, National Institute for Clinical Excellence; SWI, susceptibility-weighted imaging; DECT, dual energy computed tomography; DWI, diffusion-weighted imaging; CTA, CT angiography; MRA, MR angiography; t-PEPSI, turbo proton echo-planar spectroscopic imaging.

be useful in providing a general overview of fractures, as well as missile trajectory and location, however, the role today is limited, particularly when CT scout views can be equally valuable. If plain films are deemed necessary, they should only be obtained if delays to CT examination and further management will not be incurred.[18]

Role of Computed Tomography

Multi-detector computed tomography scanning is now widely available and recommended as the imaging modality of choice for penetrating brain injury, allowing both vascular assessment and evaluation of the craniofacial skeleton and viscera of the head.[19] CT is advantageous over other imaging modalities due to it being readily available, able to acquire images quickly, sensitivity for head injuries and high image resolution available with thin-section acquisitions.[20–22]

A non-contrast cranial CT is typically the primary imaging for PBI, usually performed within either 1 or 8 h (dependent on the indications for imaging) of the injury occurring.[23] It is common practice to obtain slices 1 mm or less in the axial plane, scanning from the base of skull to the vertex. Axial, coronal and sagittal reconstructions are then performed at thicker intervals in soft-tissue and bone algorithms.[21,24,25] Liberal use of multi-planar reformats is advised, always in correlation with the primary axial dataset. Appropriate window-width and window-level settings for different anatomical regions should also be utilised.[19] In the evaluation of the non-contrast cranial CT, coronal reformations can improve detection and characterisation of intra-cranial haemorrhage when compared with only using standard axial images.[24] The advantages of evaluating coronal images becomes important for lesions that lie in the axial plane immediately adjacent to bony surfaces, such as the anterior and middle cranial fossa, and vertex. Wei et al.[24] found that several foci of intra-cranial haemorrhage oriented transversely in the axial plane were found to be completely invisible on the axial images alone. CT is limited in the evaluation of the posterior fossa, middle cranial fossa and inferior frontal lobes, as Hounsfield artefacts can obscure these anatomical locations. Therefore, it is suggested that coronal and sagittal CT reconstructions also be performed to provide more detailed evaluation of these areas, due to anatomic continuity on these additional reconstructions.[25]

Some radiology departments perform repeat CT examinations on patients to monitor changes in injuries, in particular vascular or infectious complications,[26] however, repeat imaging is not routine and should be undertaken at the request of neurologists or other appropriate clinicians. Doddamani et al.[27] found new lesions were present in 5.5% of the second and third CT scans, and observed a change in management in 23% of patients, of which almost half the changes were due to radiological differences alone. However, a recent meta-analysis concluded that repeat CT in traumatic brain injury patients changes the management in only a minority of patients, hence the use remains controversial.[28]

CT has become the foundation of imaging in patients with PBI, as it is far superior to skull radiographs in the detection of fractures, and has a very high specificity and sensitivity for the detection of significant intracranial lesions.[12] It is also valuable in the acute trauma setting due to its rapid scan times and compatibility with life support and monitoring devices, unlike the potential difficulties associated with MRI.[24,29]

Dual energy computed tomography

Most PBIs involve large, metallic objects that generate an artefact on CT that can obscure anatomy, which is not optimal when planning surgical intervention.[30] Dual energy computed tomography (DECT) is less vulnerable to artefacts and provides images with a higher signal-to-noise ratio, thereby improving diagnostic performance.[31] It utilises two different energy settings simultaneously, high (140 kVp) and low (80 kVp) with rapid alternation between the two, which allows for the differentiation of materials based on their attenuation characteristics (Fig. 1).[31]

Role of MRI

MRI plays an important role in the PBI workup, providing an extensive and precise evaluation of tissue status. MRI is more sensitive than CT, both acutely and later post-injury, in the detection of haematomas, haemorrhages and white matter injuries such as diffuse axonal injuries (DAI) which affects a greater area of the brain.[8,33] DAI is common following PBI and is characterised by scattered microscopic white matter lesions and frequently associated with deep micro-haemorrhages often not visible on CT or conventional MRI.[34,35]

Although MRI is superior to CT in detecting these abnormalities, it is time-consuming, contraindicated if ferromagnetic objects are present and difficult to perform on unstable or ventilated patients, therefore is generally not recommended for acute imaging.[33] Monitoring equipment is often bulky and not compatible with this imaging modality, generating safety risks and sources of inference, however, new safety guidelines have been developed to categorise equipment as either *MR*
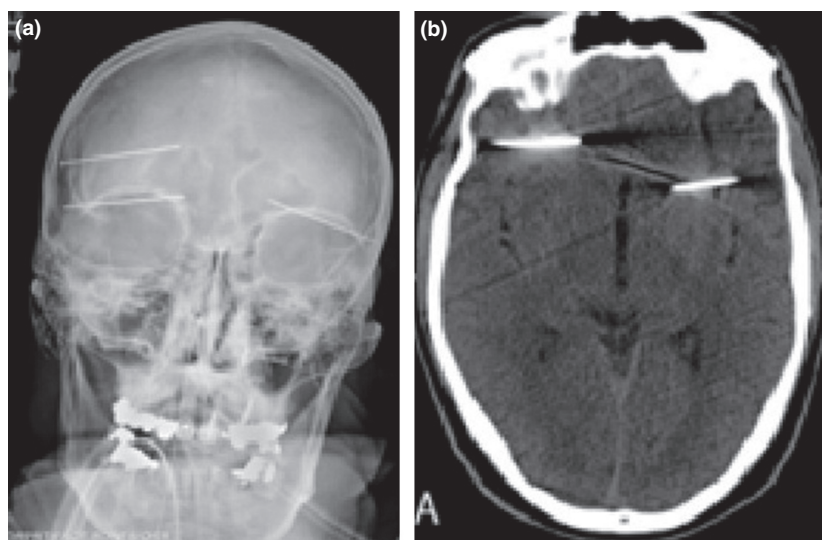
Figure 1. (a) AP skull radiograph showing three metal nails. (b) Axial non-contrast CT of the same patient. Note the metallic artefact.[32]

Conditional, *MR Safe* or *MR Unsafe*.[36] As a result, MRI is more useful in the sub-acute setting (usually performed 48–72 h post-PBI) where it plays an important role in investigating secondary brain injury, which ultimately predicts patient prognosis and long-term effects, and provides rehabilitation guidance.[23,37]

There are times when MRI is essential for primary injury identification, for example the detection of wooden or non-metallic foreign bodies, for which CT is far less sensitive. This can be better achieved using gadolinium-enhanced MRI, which can include a T2-weighted gradient-recalled echo (GRE) sequence.[2,4] Cases have been reported where wooden foreign bodies may have been missed if contrast-enhanced MRI was not performed, as shown in Figure 2.[38,39]

However, both CT and conventional MRI often lack the ability to determine long-term outcomes for patients and may miss subtle brain injuries, hence a number of alternative MR sequences are becoming increasingly useful in PBI imaging, with the benefit of increased sensitivity or faster scan times.[40] These alternatives each have their advantages and disadvantages but generally provide better evaluation of brain structures, in particular white matter. These MR sequences include.

Susceptibility-weighted imaging

Susceptibility-weighted imaging (SWI), also called axial T2* or GRE is an MR sequence primarily used to detect haemorhage.[41] SWI enhances the paramagnetic properties
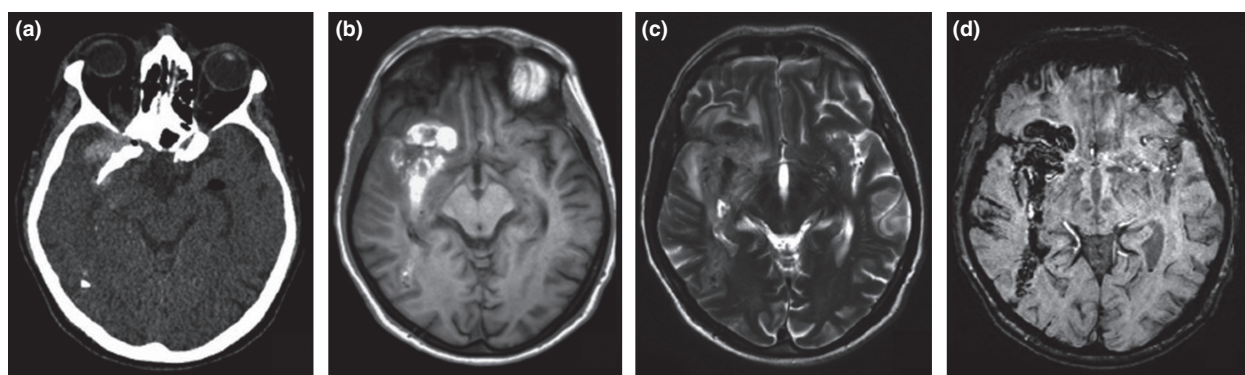

Figure 2. Wooden penetrating foreign body, (a) Axial non-contrast CT; (b) Axial spin-echo Tl-weighted MRI; (c) Axial fast-spin echo T2-weighted MR and (d) SWI imaging of the same patient.[39] A wooden object has passed through the orbit, into the parieto-occipital region, abutting the inner aspect of the skull. Note the application of SWI imaging to demonstrate the tract. MRI, magnetic resonance imaging; SWI, susceptibility-weighted imaging.

of blood products such as haemoglobin and haemosiderin.[42] These paramagnetic substances disrupt the homogenous magnetic field, intentionally introducing a signal void artefact. This allows better evaluation of intraventricular and subarachnoid haemorrhage, and DAI which are commonly associated with micro-haemorrhages not visible on conventional MRI.[35,40,43] This allows better detection of micro-haemorrhages that may otherwise go undetected.[35,40] SWI has been shown to be more sensitive than CT at detecting subarachnoid haemorrhages, with 88.4% sensitivity compared to 73.5% for CT, and tends to reveal more micro-haemorrhages than conventional GRE.[43,44] Furthermore, it is possible to perform SWI MR of the entire brain in ~4 min hence SWI could be performed on acute/sub-acute patients where there is high suspicion of haemorrhage.[35]

Fluid-attenuated inversion recovery

Fluid-attenuated inversion recovery (FLAIR) MR sequence produces strongly T2-weighted images with suppressed cerebrospinal fluid signal, which is achieved by using an inversion recovery gradient that nullifies the signal of water.[41] FLAIR is the primary MR sequence used in neuroimaging capable of detecting brain contusion, oedema, subarachnoid and intraventricular haemorrhage, and particularly sensitive to the frontal-parietal and temporal-occipital regions, and has been shown to give 100% detection of subarachnoid haemorrhages when used in combination with SWI.[43,45,46]

Turbo proton echo-planar spectroscopic imaging

Turbo proton echo-planar spectroscopic imaging (t-PEPSI) is an extremely fast MR sequence capable of detecting DAI with high sensitivity and no significant difference in lesion detection when compared to conventional GRE MR sequence.[47] Hence, t-PEPSI may be an alternative to conventional MRI in assessing DAI in uncooperative, claustrophobic or medically unstable patients.

Diffusion-weighted imaging

Both hypoxia and oedema are common following PBI and diffusion-weighted imaging (DWI) is useful in predicting regions of the brain undergoing infarction and regions of diffuse axonal injury. It measures micro-movements of water molecules in three directions, to quantify the extent of structural changes in the white matter.[48] Paired magnetic fields gradient pulses are applied, one causing protons to lose phase coherence, and therefore decrease

the MR signal, while the other gradient of opposite magnitude rephrases spins. Rephasing of protons that have moved during the time interval between the paired gradient pulses will result incomplete T1 relaxation and therefore reduced MR signal.[40] Therefore, regions of increased molecular motion results in signal loss appearing as a hypo-intense signal, whereas decreased molecular motion causes little to no signal loss, and therefore appears as hyper-intense on DWI images. Hence, regions of infarction show up as hyper-intensities. In contrast, loss of neural cell organisation causes increased diffusivity appearing as a hypo-intense signal.[33,40]

Diffusion tensor imaging

Diffusion tensor imaging (DTI) reconstructs DWI data and measures micro-movements of water molecules in three orthogonal directions,[34] thereby representing DWI data as a function of strength and direction of diffusion.[40,48] Displacement distances are comparable with cellular dimensions, therefore, can be used to evaluate cellular integrity, such as neural swelling/shrinking and loss of tissue organisation.[49] Loss of neural and glial cells result in increased diffusivity, representing reduced anisotropy in parallel white fibre tracts.[34] A prospective study compared the effectiveness of conventional MRI with DTI in predicting prognosis in patients that suffered traumatic brain injury 9 to 15 months earlier. DTI values for patients with an unfavourable 1-year outcome deviated more greatly from control DTI values than those patients with more favourable outcomes, suggesting DTI is useful in revealing structural changes to neural tissue during recovery.[34]

Single-shot echo-planar imaging

Single-shot echo-planar imaging (SS-EPI) is another type of DWI sequence with the benefit of shorter scan times and a high signal-to-noise ratio, however, it has lower spatial resolution, making it less capable of detecting microstructural changes.[40]

Role of Angiography

Vascular injury to the head is a potentially life-threatening condition that results in ~20% to 30% of all PBIs.[50,51] Vascular injuries following PBI fall into three main categories: arterial dissection, subarachnoid haemorrhage and traumatic intracranial aneurysms.[8,20] Rapid and accurate diagnosis of vascular injury is an integral stage of imaging, as emergency intervention may be needed to prevent potentially fatal neurological sequelae.[52]

Cerebral angiography is strongly recommended in PBI patients with an increased risk of vascular injury. Confirmation of a fracture near the carotid canal signifies a 35% chance of dissection of the internal carotid artery.[53] Other increased risk factors are the trajectory crossing dural compartments, Sylvian fissure, supraclinoid carotid artery, the vertebrobasilar vessels, the cavernous sinus region or the major venous sinuses.[9] An initial negative angiogram may not always be conclusive as vascular injuries may have a delayed onset, manifesting weeks or months after the trauma.[8] If suspicion is maintained, or there is a development of an unexplained subarachnoid haemorrhage or delayed haematoma, further angiography would be recommended.[7,9]

Diagnosis of vascular injury to the brain following PBI can be made using conventional CT or MR angiography. Conventional angiography is an invasive procedure with a potential risk of severe complications, including thrombosis of the femoral artery, arterial spasm and ischaemia in 0.16–2% of cases.[54] The procedure may take up to an hour, which is questionable for unstable trauma patients and has therefore been recently superseded by CT angiography (CTA).[4,18,55] CTA demonstrates the course of the foreign object in relationship to the cerebral structures of the brain and any possible vascular injury.[5] Added benefits to CTA involve the wide availability of CT scanners, it is minimally invasive and has a short acquisition time (<1 min). Disadvantages compared to conventional angiography include potential degradation of image quality from artefacts, and no possibility of therapeutic intervention directly after diagnosis (Fig. 3).[54]

MR angiography (MRA) and CTA have been shown to be equivalent in the detection of carotid and vertebral artery dissection,[57] luminal narrowing, pseudo-aneurysm formation and vessel occlusion.[58] MRA is useful in stable patients with a moderate-to-severe allergy to iodinated contrast and/or younger patients undergoing a high volume of imaging due to the absence of ionising radiation.

Imaging Pathway

Based on current literature, an imaging pathway has been devised that aims to guide radiographers and other health-care providers through managing an adult patient with penetrating brain injury (Fig. 4). The CCHR and NICE have proposed a number of clinical criteria to distinguish between patients who need urgent investigation with CT (within 1 h) and those in whom CT can be performed within a 'reasonable period'.[13] Patients are categorised into two risk factor groups based on the recently updated NICE Guideline,[14] which has incorporated risk factors from the CCHR Guideline, and this determines the urgency of imaging. If 'high risk factors', such as a GCS less than 13 on initial assessment or suspected depressed skull fracture, are recognised then CT imaging is performed within an hour of presentation to the emergency department. If a patient presents with one or more of the 'medium risk factors', that is retrograde amnesia of more than 30 min, dangerous mechanism of injury or age >65 years, the CT scan can be performed within 8 h of admission.[14] For both risk categories, a "provisional radiology report should be made within 1 h of the scan being performed" (pp. 24).[14] It is important to note than the CCHR guidelines are not applicable for non-trauma patients, or those with a GCS < 13, bleeding disorder, or obvious open skull fracture, as neurological intervention is to be expected.[13]
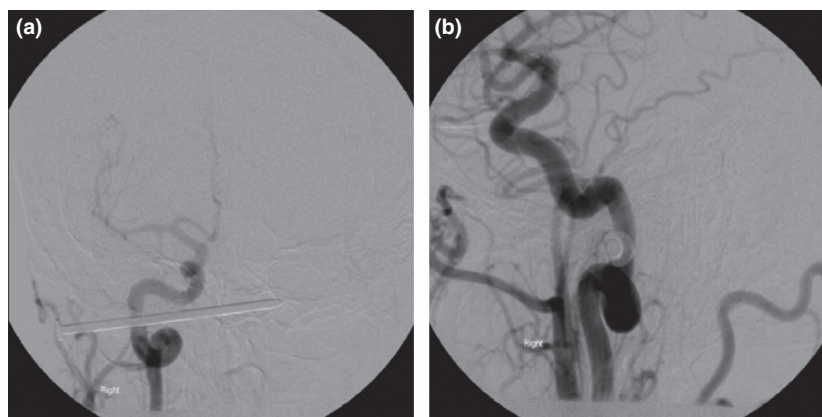
Figure 3. Self-inflicted nail-gun injury to the head. Anterior (a) and lateral (b) right internal carotid angiograms demonstrating focal narrowing of the right internal carotid artery as it runs adjacent to the nail with no extravasation. The nail appears to be causing some focal pressure or vasospasm on the artery at the level of the foramen lacerum with no perforation.[56]
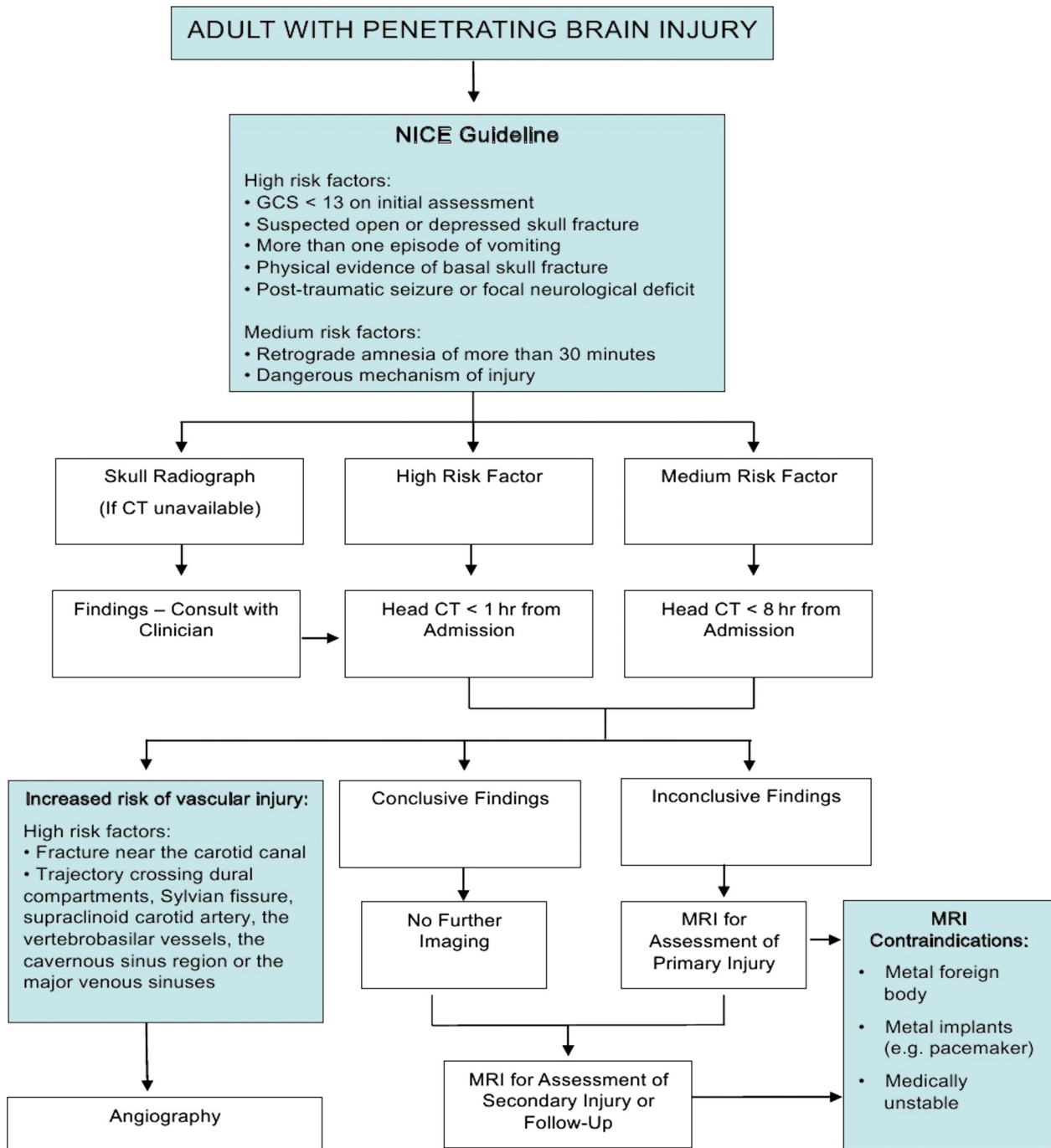
Figure 4. Diagnostic imaging pathway for adult patient with penetrating brain injury. GCS, Glasgow Coma Scale.

The clinical outcome from the CT imaging can then lead to one of three courses. Firstly, if vascular involvement is suspected where injury may be near the carotid canal or the trajectory crosses particular regions of the brain, then CT, MR or conventional angiography is recommended. Secondly, if conclusive findings are made then no further imaging is immediately required. Thirdly, if inconclusive findings are made from the CT imaging then a MRI scan is recommended for assessment of the primary injury. This is provided that the patient does not have any contraindications, such as metal objects that may be present, or if the patient is unstable or ventilated.

MRI can also be utilised for follow-up or diagnosis of secondary injuries at a later stage of patient care despite conclusive findings being made.

Conclusion

PBIs are a unique form of traumatic brain injury that necessitates an interdisciplinary diagnostic and therapeutic approach. Neuroimaging plays an integral role in the evaluation and management of an adult patient with penetrating brain injury, providing assessment of potentially life-threatening injuries and patient prognosis. Currently, non-contrast CT and CTA retain the principal role of imaging in the acute setting, due to rapid image acquisition, high sensitivity, fewer contraindications and availability in most radiology departments. MRI and MRA are primarily used to complement findings acquired from CT, however, with the development of faster scan times and MRI-compatible resuscitation equipment, in combination with the greater sensitivity MRI provides in detecting brain injury and repair, it is expected that MRI and MRA will become more accessible and beneficial in the acute detection of adult PBI in future. This review demonstrates an imaging pathway that uses relevant modalities in a logical order to evaluate the extent of injury to an adult with a PBI. Rapid and precise diagnosis of the patient's neurological status is paramount in correctly managing the condition for the best possible medical outcome.

Conflict of Interest

The authors declare no conflict of interest.

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