

Radiological Imaging in Infant Non-Accidental Injury

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Received: November 22, 2015 Revised: February 1, 2016

Accepted: February 3, 2016

Published online: March 7, 2016

ABSTRACT

In the UK, seven percent of children will have experienced serious physical abuse from their primary carers at some point during their childhood. Appropriate and effective imaging techniques can drastically improve diagnosis of resultant non-accidental injury (NAI) from child abuse. This includes suitable imaging modality choice and techniques set out by expert opinion and clinical guidelines, such as the standards for radiological investigations of suspected non-accidental injury produced by the Royal College of Radiologists (RCR) in collaboration with the Royal College of Paediatrics and Child Health (RCPCH). There are certain markers that are almost diagnostic of NAI, for example classic metaphyseal lesions or subdural and retinal haemorrhage with encephalopathy. Effective evaluation of these findings by a capable radiologist will lead to accurate and efficient diagnosis and management. Furthermore, an awareness of potential radiological mimics of NAI is vital for appropriate diagnosis. If this is achieved successfully, radiologists and other members of the multidisciplinary healthcare team can have a direct, positive impact on effective management of these sensitive cases.

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Key words: Non-accidental injury; Shaken baby syndrome; Child

abuse; Interhemispheric subdural haematoma; Classic metaphyseal lesions; Diaphyseal fractures

Marshall M. Radiological Imaging in Infant Non-Accidental Injury. *International Journal of Radiology* 2015; 3(1): 72-81 Available from: URL: <http://www.ghrnet.org/index.php/ijr/article/view/1487>

INTRODUCTION

NAI is the resultant injury, intentional or not, to an infant because of abuse from their caretaker^[1]. Tragically, as much as 55% of fatally abused children have been seen by a healthcare professional in the last six months^[2]. If NAI is missed in a differential diagnosis the probability of further abuse greatly increases, which may result in mortality to the infant. Particularly vulnerable groups to child abuse include adopted or fostered children, children with disabilities, and younger and pre-mobile children who are less susceptible to accidental injury while also being more prone to bone fracture^[2]. In England, child abuse causes one to two infant deaths every week; this figure may be even more given the ambiguity and illicit nature of child abuse cases^[3].

On a public health level, the National Institute for Health and Clinical Excellence (NICE) produced clinical guidelines in 2009 to improve awareness and effective management of child abuse^[4]. They included three core concepts:

- (1) 'Alerting features' of signs and symptoms and patterns of injury and behaviour of child abuse;
- (2) To 'consider' child abuse as a cause to these alerting features;
- (3) Toproactively 'suspect' abuse in order to highlight the serious concern required for child abuse cases.

The most common types of non-accidental radiological findings include bone fractures, haematomas, haemorrhages and contusions. The specificity that a particular injury or finding is abusive varies according to which bone is fractured and the location of haematomas, haemorrhages or contusions. An inconsistent history of events is perhaps the strongest indicator of NAI when in conjunction with appearance of these findings.

The severity of child abuse and non-accidental head injury (NAHI) is stark. In America, NAI is an increasingly frequent cause of central nervous system (CNS) injury and is estimated to account for 80% of all infant CNS injury deaths, roughly 3,000 deaths per annum^[5]. The peak incidence of NAHI is in six-month-old babies^[5]. Figures in the UK show NAHI results in overall mortality in 20% of cases and severe disability in 34% (25% of children will develop mild disability)^[2]. The likelihood of a worse outcome and frequency of NAHI is more common, the younger the infant. The annual incidence of NAHI in the UK is 36 per 100,000 children less than six months of age^[2]. The high incidence combined with inflated rate of mortality and morbidity underline the severity of this problem. There is a spectrum of CNS findings that strongly indicate NAHI. These highly explicit findings have been classified into the term 'shaken baby syndrome' (SBS) to assist radiological assessment and clinical diagnosis. A systematic review of relevant literature concerning clinical and radiological findings in NAHI found subdural and retinal haemorrhages, encephalopathy such as cerebral ischaemia and oedema, intra-cranial injury, fractures of the skull, metaphyses, long bones and ribs, bruising, seizures, apnoea and an inadequate history of events to be the strongest indicators that a head injury was inflicted^[6].

However, there can also be false indicators of NAI presenting in radiological images. Potential impersonators of NAI include hypoxic-ischaemia, ischaemic injury, seizures, infections or post-infectious conditions, coagulopathy, fluid-electrolyte imbalance, metabolic disorders and connective tissue disorders^[7]. Conditions leading to failure to thrive and causes of accidental injury, such as epilepsy or road traffic accidents, may also have the potential to present as indicative NAI skeletal pathology in images^[3]. Furthermore, glutaricaciduria rarely causes subdural haematoma^[3] but should still be considered in differential diagnoses.

The implications of NAI misdiagnosis are massive to the infant and carers as well as potential consequences to healthcare professionals. Therefore, it is paramount to present a differential diagnosis including suspected NAI and any possible mimics of NAI as presented in radiological images.

SHAKEN BABY SYNDROME

A modern definition of SBS from the British Medical Journal (BMJ), 2004 states; "Shaken baby syndrome is a form of physical non-accidental injury to infants, characterised by acute encephalopathy with subdural and retinal haemorrhages, occurring in a context of inappropriate or inconsistent history and commonly accompanied by other apparently inflicted injuries."^[8, p720]

In 1946, John Caffey published a famous paper researching into multiple long bone fractures and chronic subdural haematoma^[9]. He concluded; "fractures of the long bones are a common complication of infantile subdural hematoma."^[9, p758] This unusual association formed the foundation to the SBS first coined by Caffey. He postulated a 'whiplash' mechanism of non-traumatic rapid shaking in the abused infant to be the primary cause of encephalopathy, subdural haematoma (SDH) and retinal haemorrhage (RH) which are the three key components or 'triad' of SBS^[9]. Figure 1 illustrates this mechanism accurately and also presents the resultant NAI that can occur such as the combined triad, rib fractures and classic metaphyseal lesions. This concept defied the previously believed traumatic causative theory. However, gradually Caffey's hypothesis for SBS established itself as the most widely held and accurate mechanism for non-accidental CNS injury and associated skeletal NAI. The young infant is especially vulnerable to these sudden angular accelerating and decelerating forces because of weaker



Figure 1 Shaken baby syndrome mechanism with resultant classic metaphyseal lesions, rib fractures and CNS injuries^[18].

neck muscles, a larger head and an immature brain^[7]. Radiological appearances of the combined triad is now often utilised incorrectly by doctors as being wholly indicative of NAI such as the influence of Caffey's postulate^[10]. Modern restatements of SBS such as the definition from the BMJ include the context of an inconsistent history and neck or spinal cord damage to further reinforce the suspicion for child abuse^[7, 8]. Fundoscopic examination of the retina may reveal RH, however, this is not a radiological investigation therefore shall not be covered. SDH and encephalopathy (such as hydrocephalus) may be exposed accurately by a CT or MRI of the head. This should be performed following radiological guidelines, for example the NAHI imaging algorithm presented in figure 8. A typical inflicted SDH in the posterior interhemispheric fissure is demonstrated by the CT head scan in figure 5.

Despite the general acceptance of Caffey's theory by the medical profession there is still some controversy to the actual mechanism producing the combined triad. It is generally accepted that there are multiple mechanisms for NAHI for example battering, shaking (SBS), impact, strangulation, suffocation and any combination of these mechanisms^[11]. The controversy in SBS, however, mainly involves uncertainty about precise causation and the magnitude of forces required and whether impact is necessary as well^[8]. Recent research suggest cerebral hypoxia and raised intra-cranial, arterial and central venous pressures can cause SDH and RH and not traumatic shearing of subdural or retinal vessels from rapid non-traumatic shaking^[10]. This data casts doubt on Caffey's mechanism and has had notable effects in medico-legal cases^[8, 10]. Furthermore, dispute surrounds the rhetoric of the term 'shaken baby syndrome' as it contains investigative implications which some argue should be beyond the scope of doctor's solely medical perspective^[10]. They claim there should be clear distinction between a doctor's medical diagnosis – which in this case would be 'multiple fractures', haemorrhage or encephalopathy – and social health worker's investigations. The debate surrounding the exact mechanism for non-accidental CNS injury is important as it has clinical radiological repercussions, for example the location and morphology of intra-cranial haemorrhages and co-existence with gripping injuries such as bone fractures. However, regardless of precise mechanisms for SBS, there are certain radiological indicators such as SDH that are generally agreed to be virtually diagnostic of NAI. This highlights the worth of good radiological investigations to effectively assist child abuse cases and NAI diagnosis.

IMAGING MODALITY

To accurately diagnose NAI and assist its identification, radiology plays a fundamental role. Many questions stem from radiological investigations in NAI such as: What findings are particularly indicative of NAI and what imaging modality is most appropriate to reveal these findings? How can appearance of such findings assist diagnosis and confirm any suspicion or presumption of NAI? How can one distinguish between definitive findings of NAI in radiological images from possible mimics? And finally, what are the currently set out clinical guidelines for skeletal or neurological imaging to efficiently and effectively detect NAI?

X-RAY

Skeletal injury is the second most prevalent finding in child abuse cases after cutaneous findings such as contusions or bruising^[12]. Therefore, it is by far the most common and important radiological discovery in NAI. Resultant non-accidental fracture is reported to occur in between 11% to 55% of cases of child abuse^[13]. The large variation is accountable to the age and medical state of the child and type of populations analysed. X-ray is the traditional and, usually, first imaging modality choice in suspected NAI. Skeletal imaging is performed to detect occult bone injuries, gain more information regarding a clinically suspected injury, date bone injuries and assist diagnosis of NAI mimics that could be caused by skeletal disorders^[2]. A skeletal survey provides multiple radiographic images to visualise the whole infant skeleton^[14]. This requires imaging the skull, chest (obliquely and antero-posteriorly), abdomen, pelvis, spine and both humeri, forearms, femora, lower legs, hands and feet^[2]. Skeletal surveys are deemed necessary in all suspected child abuse cases^[12] and should always be performed in children under two when NAI is suspected according to the RCR and RCPC clinical guidelines^[2]. The guidelines further state skeletal survey should be the standard initial imaging method and first imaging investigation in suspected NAI^[2]. Additionally, repeat skeletal imaging is recommended^[2] and valuable to assist diagnosis as it can show appearance of healing injuries that were not previously seen^[15]. A babygram images the entire infant skeleton on a single image but it is not advised or recommended as a substitute for the skeletal survey because of geometric distortion and differing exposures across the body^[2, 16].

Scapular, spinous process and sternal fractures are highly specific for NAI as they are difficult to break^[12, 15, 16]. However, the incidence of these fractures is rare so its clinical utility is limited. Classic metaphyseal lesions and rib fractures are also explicit in NAI^[12] and their incidence is much greater so are extremely valuable clinically for NAI inclusion in a differential diagnosis. Shaft fractures have a low specificity for NAI^[12] but because of their high incidence NAI should still be considered when they appear, particularly in conjunction with an inconsistent history such as in a non-ambulatory patient with a spiral fracture of the femur. Additionally, the specificity of skull fractures for NAI is only moderate^[12] but its severity and frequent co-existence with other more explicit findings warrants NAI consideration. Other skeletal injuries with moderate specificity justifying NAI consideration include epiphyseal separations, vertebral body fractures and subluxations, digital fractures as well as multiple fractures and fractures of different ages implying repeated occurrences of child abuse^[12, 15].

Classic metaphyseal lesion (CML)

The CML—originally termed by Caffey as ‘bucket-handle’ or ‘corner’

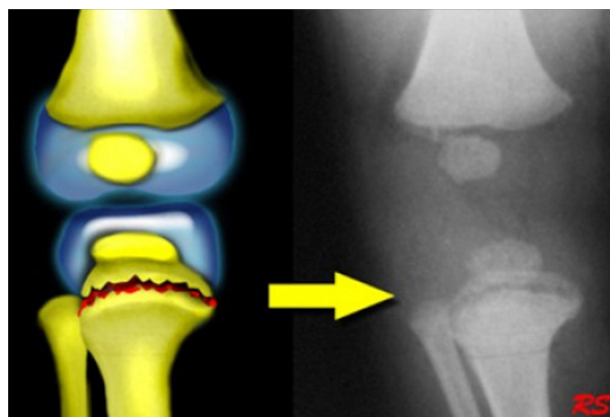


Figure 2 CML of the proximal tibia presenting as a ‘bucket-handle’ fracture shown in the diagram on the left and in an example on an X-ray image to the right^[18].

fractures^[12, 15]—is the most common non-accidental skeletal finding in young children^[15]. CMLs typically present on radiographic images perpendicular to the long bone while aligning itself parallel to the growth plate, differential horizontal motion may feature along the metaphysis^[16]. It occurs in 39-50% of abused infants less than 18 months old^[17] and is effectively pathognomonic of NAI. It can present in any major long bone but most commonly the tibia, distal femora and proximal humeri, it usually occurs bilaterally^[12, 15]. Caffey’s SBS mechanism is the widely accepted mechanism of injury for metaphyseal fracture rather than a direct impact mechanism^[13, 15]. The angular shaking forces cause a shearing force at the metaphysis resulting in fracture^[12]. CMLs are mainly osseous but fracture lines can extend to cartilage and growth plates if the shaking is severe enough^[15]. The appearance of a ‘bucket-handle’ or ‘corner’ fracture on radiographic images essentially depends on the X-ray axis of orientation^[15], although ‘bucket-handle’ fractures tend to have a larger fragment of bone avulsed^[18]. Figure 2 demonstrates how a tibial CML can present as a ‘bucket-handle’ fracture when imaged ‘en face’ to the fracture line by the X-ray beam, the location of the fracture line in the radiographic image in figure 2 is illustrated in the adjacent diagram. A ‘corner’ fracture is exemplified in the pictorial in figure 1 at the lateral margins of the femur, while the ‘bucket-handle’ fracture is shown in the middle. It is important to note that both ‘bucket-handle’ and ‘corner’ fractures are CMLs but vary in location, size and appearance on radiographic images.

Shaft fractures

Diaphyseal fractures are the most common non-accidental skeletal finding overall but generally have low specificity for child abuse because they commonly occur accidentally^[12, 15]. In the case of NAI, the mechanism of injury is usually direct impact or torsional forces to the infant’s extremities^[15]. Unfortunately, because there are no highly specific inflicted shaft fractures it can be difficult to radiologically assist NAI diagnosis in shaft fracture appearance^[13]. To counter this, inconsistent or inappropriate histories and co-existence of other more specific fractures can reaffirm child abuse suspicion^[13]. Additionally, shaft fractures in pre-mobile children should raise suspicion as the fracture is far less likely to be accidental^[12]. Figure 3 presents a particularly severe femoral shaft fracture. The severity of the fracture in conjunction with the young pre-mobile age of the infant strongly indicates child abuse which was later confirmed. Also note the growth plates at the distal and proximal ends of the femur and tibia respectively. CMLs align themselves along growth plates perpendicular to the bone which may lead to confusion between



Figure 3 Lateral view of a spiral midshaft right femoral fracture under X-ray raising NAI suspicion^[17] (a bone scan of the same patient is presented in figure 9).



Figure 4 AP X-ray image of the chest of a child having undergone NAI showing multiple posterior rib fractures (arrows)^[19].

the radiographic appearance of growth plates and CMLs. However, growth plates will not exhibit differential motion. Presentation of growth plates with CMLs is shown in figure 2, which demonstrates the difference between the two.

Rib fractures

Rib fractures are a very common and highly explicit radiological finding in NAI. Posterior rib fractures have the highest specificity for child abuse^[13] because in abusive shaking the chest is squeezed causing the ribs to break close to their attachment to the vertebrae^[18]. In younger infants the NAI specificity of rib fractures is greater as their ribs are more deformable so fracture less often resulting in few cases of rib fracture in young children^[12], therefore when one does present the suspicion for abuse must be more serious. Additionally, fractures of the first rib are more definitive of abuse because greater forces (compression) are required to fracture it^[12]. The mechanisms of injury in inflicted rib fracture is thoracic compression^[15]. Antero-posterior compression will result in lateral fractures while lateral compression will cause anterior or posterior fractures^[13]. They usually present as multiple fractures with adjacent ribs and are often contralateral^[15] such as in figure 4, which is pathognomonic because of the presence of multiple contralateral, posterior rib fractures. There is difficulty viewing rib fractures by X-ray as fracture lines can be hidden by superimposed soft tissue and vertebral transverse processes^[15]. Furthermore, the obliquity of rib fractures means it is often difficult to align the X-ray beam with the fracture line^[13]. This is why additional oblique views of the chest are a necessity in skeletal surveys^[2]. Notable accidental causes of rib fracture include birth injury, metabolic disorders, bone dysplasias and major trauma^[12, 13]. This can be problematic in radiographic images as it could lead to NAI misdiagnosis. Like with shaft fractures, an inconsistent history and co-existence with other specific NAI findings must be acknowledged to assess NAI suspicion and deduce the correct diagnosis. Cardiopulmonary resuscitation can occasionally produce anterior rib fractures but will not cause the more specific posterior rib fractures so is therefore a highly unlikely mimic of abusive injury^[17].

COMPUTERISED TOMOGRAPHY

Radiological investigation of NAHI has revolutionised over recent decades. Radiologists are now even more crucial in the identification and diagnosis of infant NAHI. CT is primarily used for CNS injury, the most severe and life-threatening NAI. It is the modality of choice in SBS^[20] and is particularly adept at detecting acute haemorrhage, oedema, skull fracture and scalp injury^[5]. In NAHI, a CT head scan is the usual initial imaging investigation^[1] even though it is mostly inferior to MRI for detecting indicative abusive head injury findings. It is the first point-of-call radiologically, however, because of its widespread availability, relative accessibility to the young patient and short time to scan (especially if the recommended multi-slice CT is used). It is notably superior over MRI in detection of acute blood such as SDH which would require immediate neurosurgical intervention^[1] – a rare but serious event. This valuable ability has significantly improved NAI diagnosis and outcomes for abused infants because small SDHs are so common and indicative of child abuse. In today's times of cost-effectiveness within the NHS, its inexpensive cost compared to MRI is a major advantage. Computed tomographic angiography or venography can reveal the causation of a haemorrhage or infarction^[7]. CT can differentiate between subarachnoid and subdural haematoma although MRI is preferred as its distinguishing ability is superior^[7]. A drawback of CT scanning is the significant exposure of radiation to the more vulnerable young patient with risk of induced cancer. The benefits of CT investigations must be balanced to these risks and outweigh them. Recent technological advances mean low-dose techniques and automatic regional changes to radiation during scanning is now available for infants to reduce the radiation exposure^[16]. CT findings are insufficient to elucidate patterns of injury and timing therefore differential diagnoses and other imaging investigations are necessary^[7]. There are many other causes of apparent extra-cerebral blood accumulations presenting on CT scans not from NAI therefore a differential diagnosis should consider multiple factors. Similarly with X-ray imaging, repeat scans are highly useful clinically. Repeat CT head scans can reveal surgical changes such as healing fractures,

changes to recurrent haemorrhages (redistribution) or appearance of new haemorrhages, and evolving cerebral densities indicating chronicity of intra-cranial haemorrhages^[7].

Interhemispheric subdural haematoma

Intra-cranial haemorrhages following shearing of cerebral vessels are “unilateral or bilateral high-density collections of fresh blood that are thin but extensive”^[20, p1823]. Inflicted SDHs occur from rotational brain movements or shearing forces during abuse^[16]. Blood tends to drain into the posterior interhemispheric fissure^[1]. CT head scans are particularly suitable to clearly display interhemispheric SDHs as shown in figure 5. A study on the application of CT in abusive craniocerebral injury found that 67% of infant patients presenting with interhemispheric SDH had a history of being shaken^[21]. While this is not diagnostic of NAI, the high prevalence and severity of SDH warrants cause for concern. The same study also found that of those patients presenting with acute interhemispheric SDH, all of the patients will later develop cerebral atrophy and in 50% of cases it leads to cerebral infarction^[21]. Additionally, 80% also had retinal haemorrhage supporting the combined SBS triad^[21]. The severe consequences of interhemispheric SDH highlights the importance of CT head scans and high quality radiological assessment for rapid neurosurgical referral.

Abdominal injuries

Abdominal visceral injuries are a relatively common consequence of child abuse, reported to occur in 2-10% of abuse cases^[18]. The most common non-accidental abdominal and thus most NAI-specific injuries are adrenal bleeding, visceral perforation or haematoma and liver or pancreatic laceration^[18]. Contrast-enhanced CT is the imaging modality of choice for abdominal viscera (and thoracic viscera)^[2], it will also further reveal retroperitoneal haematomas^[16].

MAGNETIC RESONANCE IMAGING

“Magnetic resonance imaging of the brain is an essential part of the investigation of any infant with suspected non-accidental head

injury”^[22]. MRI is invaluable clinically in abusive injury and superior over CT for detection of the majority of intra-cranial injuries with the notable exception of acute blood^[15]. Furthermore, MRI poses a substantially less radiation exposure risk compared to CT or X-ray. Brain parenchymal injuries therefore present more clearly on MRI. Common inflicted parenchymal injuries include shear injury, oedema and contusion^[2, 16]. Subacute and chronic intra-cranial haemorrhages are detected and more accurately mapped on MRI than CT^[2]. MRI can also detect small extra-axial haemorrhages that may be missed on CT scans^[16, 20]. More severe secondary brain injuries from NAI are best detected by MRI such as enlarging or chronic SDHs, hydrocephalus and leptomeningeal cysts^[2]. Additionally, for ligamentous and intraspinal NAI, MRI is deemed the most effective imaging modality^[7]. Non-accidental CNS injury can extend to the lumbar regions which is best detected by MRI. MRI is also used to date haemorrhages by detecting blood products in the accumulations^[16]. Its ability to time injuries and elucidate the pattern and extent of injury through comprehensive repeat scans – which is beyond the scope of CT – has great diagnostic and medico-legal value.

Advanced MRI techniques

There are numerous advanced MRI techniques which have unique superior abilities over conventional MRI in child abuse cases. Fluid-attenuated inversion recovery imaging can suppress CSF signal to aid identification of abnormal subarachnoid and chronic subdural collections and also acute SDH^[5, 22]. A statistical trial found diffusion-weighted imaging to be superior to standard MRI in detecting hypoxic-ischaemic brain injury such as infarction and acute ischaemic changes in infant NAHI^[1, 2, 23]. Diffusion-weighted imaging has been advised to be utilised routinely to detect “secondary ischaemic sequelae of NAHI”^[2]. T1- and T2-weighted techniques can detect the nature and timing of haemorrhages from recognised criteria^[7]. Gradient-recalled echo is superior in detecting haemorrhages or thromboses but insufficient alone to time injuries as most blood collections will appear hypo-intense^[7]. Finally, MR angiography or venography can detect vascular injury such as aneurysms or thromboses better than conventional MRI or CT^[7].

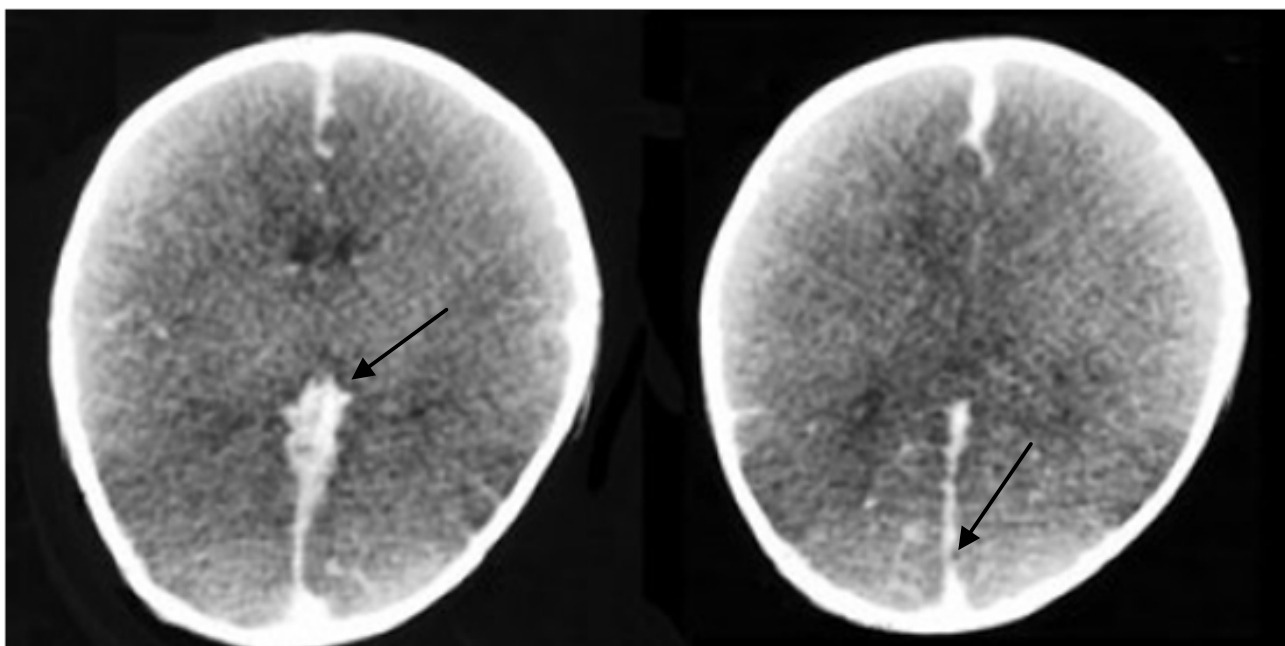


Figure 5 CT head scan of posterior interhemispheric SDH (arrows) in a fatally abused child^[18].

NEUROIMAGING RECOMMENDATIONS

Effective utilisation of CT in conjunction with MRI “enables more accurate detection, localisation and characterisation of any intracranial injury”^[2]. While CT is the standard and traditional neuroimaging investigation. MRI should be utilised in the vast majority of cases to determine prognosis, pattern and timing of injuries and provide care and protection to the infant in medico-legal cases^[15]. The RCR and RCPCCH produced an imaging algorithm for suspected NAHI presented in figure 8 to assist the radiologist in applying the appropriate imaging modality at the correct time. CT is the neuroimaging investigative modality of choice in acute presentation when an immediate detection is required for rapid

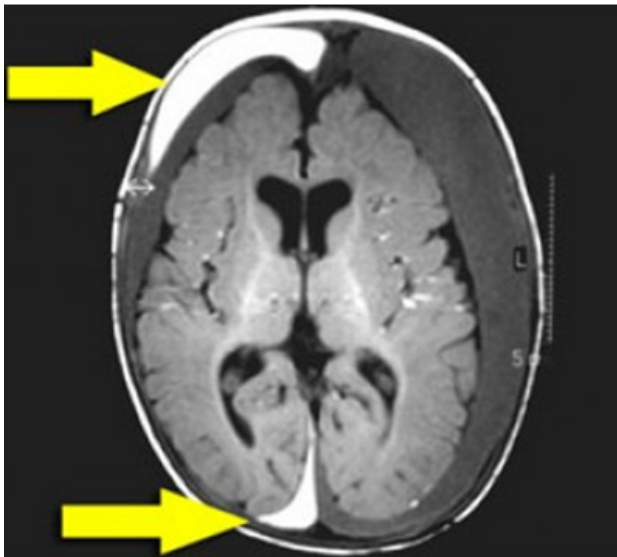


Figure 6 T1-weighted MR image showing bilateral fluid collections from chronic SDH and new SDH in the right frontal and posterior fossa regions^[18].

intervention. On the day of the patient’s admission to hospital a cranial CT should be undertaken immediately (if NAI is suspected). Following this, therapeutic tapping of the SDH is advised as it may provide information of the nature and appearance of the blood^[2]. Although the likelihood of an inflicted CNS injury to be non-acute is slim, the clinical guidelines state that in the non-acute setting when time is not a limiting factor, MRI testing for CNS injuries should be used over CT^[1].

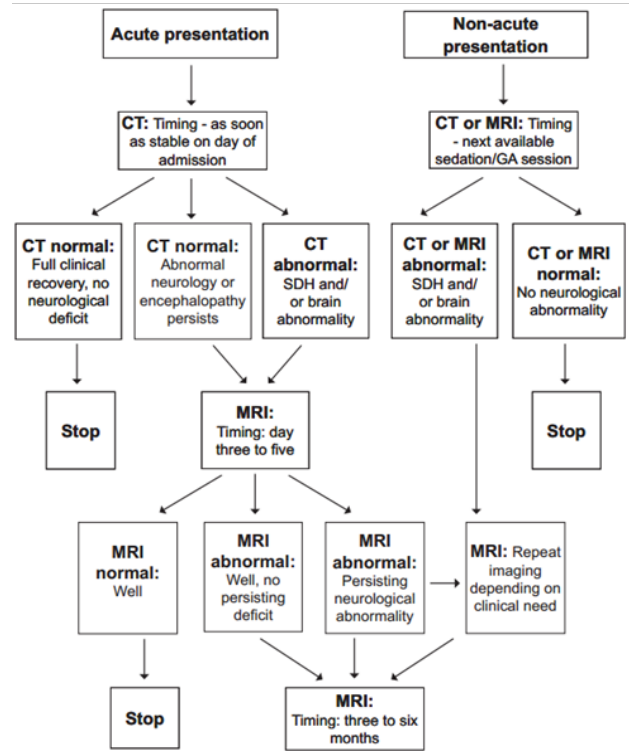


Figure 8 Imaging algorithm for suspected NAHI^[2, p35]

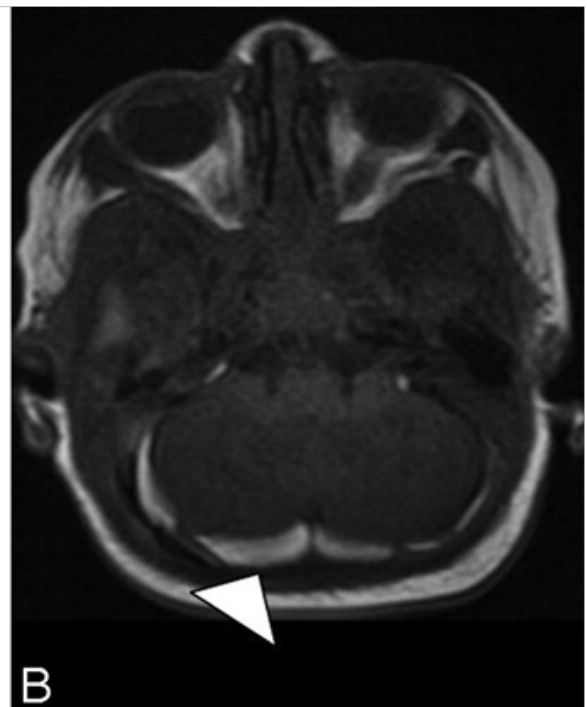
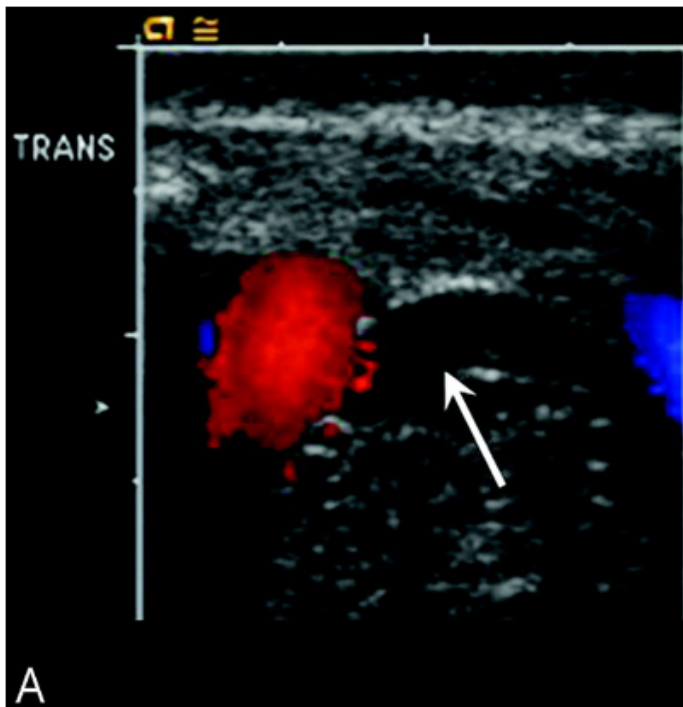


Figure 7 Posterior interhemispheric SDH shown on US (axial sonogram) to the left and on a T1-weighted MR image as a high-signal intensity on the right^[24].

OTHER MODALITIES

There are other forms which may be used to assist NAI detection. These have a notable if not major history of radiological application in NAI. The supporting evidence of these alternative investigations is less well defined, however.

Skeletal scintigraphy

Bone scans are sometimes complementary to the skeletal survey^[12, 20] and have been found to produce fewer false negatives in detecting inflicted bone injury compared to the skeletal survey^[25]. Additionally, it offers a more practical alternative than imaging the entire skeleton in an older child^[15]. This suggests there is clinical diagnostic value to skeletal scintigraphy in suspected NAI. However, it is not as sensitive

in detecting CMLs and skull fractures^[12] although possibly more sensitive for rib fractures compared to the skeletal survey^[12]. The supplementary role of bone scans is demonstrated well in the case presented in figures 3 and 9. The femoral shaft fracture revealed by X-ray in figure 3 raised suspicion of NAI which was confirmed by the rib fractures accurately exposed by the scintigraphy in figure 9. However, skeletal scintigraphy is inferior to the skeletal survey for dating injuries and has low capability to diagnose an inflicted injury from other causes^[2]. Skeletal imaging is almost always necessary to confirm any suspicion which is not the case conversely. While bone scans may have some benefits in very specific situations such as the example presented, its significant inferiority to the skeletal survey means it is generally agreed to have only a minor supplementary role in skeletal imaging of NAI^[12].

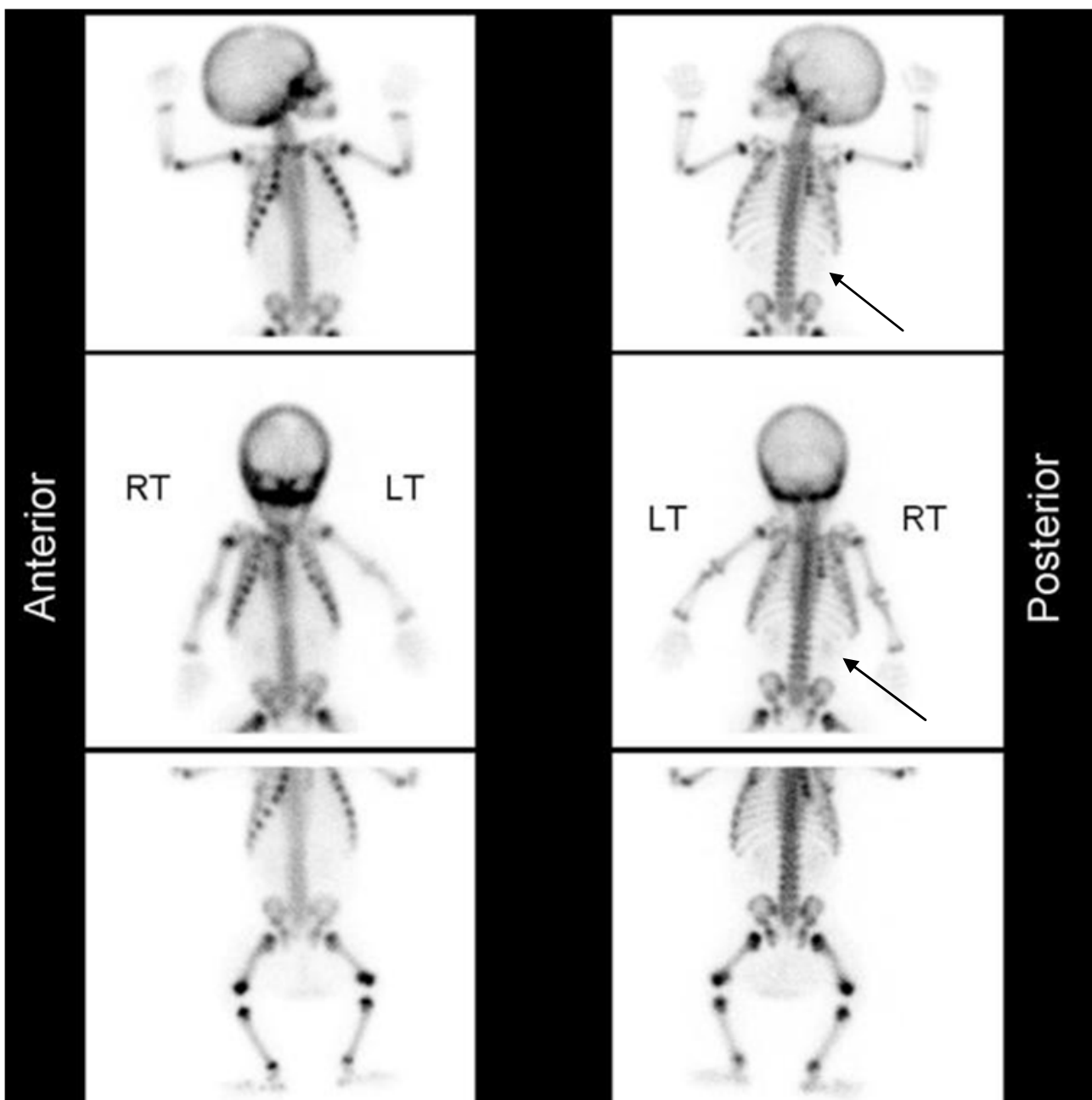


Figure 9 Bone scan of the same young patient viewed under X-ray in figure 3. Skeletal scintigraphy revealed posterior rib fractures of the right 4th to 7th ribs (viewed best by the arrows in the upper right two images), effectively confirming NAI suspicion. Lack of focal uptake on the right femur suggests the injuries may have occurred at different times unless the degree of displacement of the femoral fracture prevented osteoblastic activity^[17].

Ultrasonography

The precise role of ultrasonography (US) in the case of NAI is not defined and there is minimal evidence to support it thus far. The RCR and RCPCD do not advise it as a primary investigation in NAI^[2]. Inflicted SDHs are usually thin and widespread in the posterior interhemispheric fissure which is not well imaged by US^[11], yet figure 7 seems to contradict this as it shows ultrasonographic detection of a posterior interhemispheric SDH. However, the adjacent MR image presents the SDH much more clearly so should always be favoured over US. Head ultrasonography is therefore inoperable. Abdominal ultrasonography may be utilised to detect visceral injuries and free fluid^[16] but is still mostly inferior to abdominal CT. A unique example where ultrasonography is useful clinically is in differentiating abusive hip fracture-dislocations from developmental dysplasia of the hip^[16].

THE NAI DIFFERENTIAL DIAGNOSIS

As has been discussed in detail, the clinical diagnostic value of highly specific findings in radiological images of NAI is great and these findings have a pivotal role in the diagnosis of NAI. However, there are numerous conditions that may mimic these findings and it is of paramount importance for the competent radiologist to be able to distinguish these impersonators from genuine inflicted injury. While many medical conditions may impersonate many features of inflicted injuries, it is important to note that no condition will impersonate all the combined findings in NAI. Therefore, a detailed analysis of the various clinical and radiological findings coupled with a history of events should always lead to a definitive diagnosis: NAI or not? Other significant considerations are multifactorial causes and synergistic mechanisms simultaneously working to present as apparent NAI. Additionally, patients with these mimics can of course still be abused so a diagnosis may include NAI and the specific impersonating

disorder. It is impossible to accurately describe each and every mimic of NAI therefore only the more notable examples will be considered. Accidental injury

Accidental injury

Accidental injury is by far the most prevalent mimic of NAI^[20]. Highly specific non-abusive injuries such as epidural (extradural) or subarachnoid haemorrhages may be mistaken for SDHs – an MRI scan should correct this fault^[20]. SDHs are not exclusively inflicted, accidental SDHs may occur following road traffic accidents which may lead to NAI misdiagnosis^[20]. Birth trauma and cardiopulmonary resuscitation may sometimes cause rib fractures but this case is relatively rare^[18]. Figure 10 demonstrates presentation of a non-abusive cause to the combined triad – a rare but not impossible occurrence. The case was thought to be inflicted but later proved to have resulted from birth trauma^[11]. In accidental injury, a consistent history correlating to the symptoms combined with an absence of other NAI-specific injuries should prevent misdiagnosis in most cases^[20].

Osteogenesis imperfecta

This rare skeletal dysplasia is a relatively common mimic of abusive fractures. Type I and type IV of the disorder impersonate inflicted skeletal injuries^[16]. Non-radiological clinical features of osteogenesis imperfecta include blue sclerae, hearing impairment and bruising which may further obscure the clinician's viewpoint^[20]. The presence of osteopenia, modelling and bowing of long bones, wormian bones, dentinogenesis imperfecta, joint hypermobility, progressive scoliosis and short stature are indications that perceived skeletal NAI may instead be osteogenesis imperfecta^[16, 20]. Additionally, the location of NAI-specific skeletal injuries often differs from usual fractures seen in osteogenesis imperfecta, although the disorder leads to shaft fractures

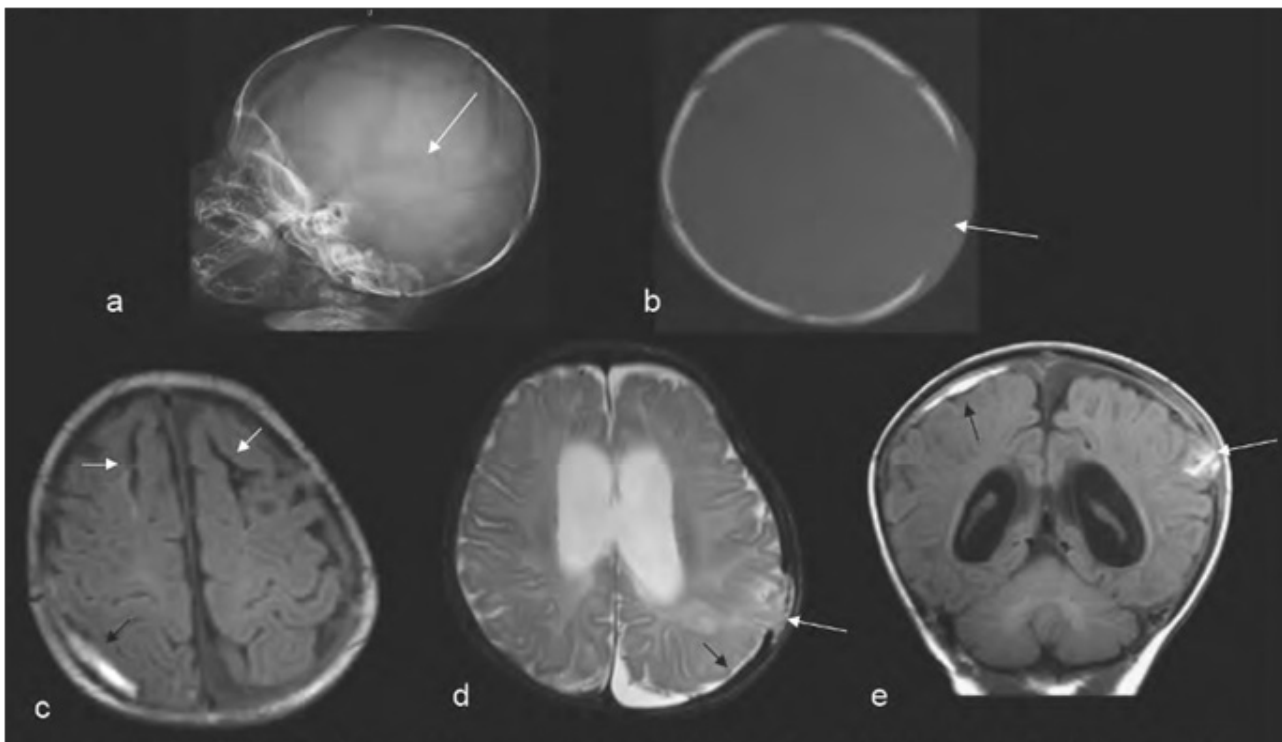


Figure 10 A skull film (a), cranial CT (b) and FLAIR (c), T2- (d) and T1- (e) MRI of a 9 week-old infant showing bilateral skull fractures (long white arrows), chronic bifrontal cerebral white matter clefts (short white arrows) and acute, subacute and chronic SDH/rehaemorrhage (black arrows) from birth trauma^[11].

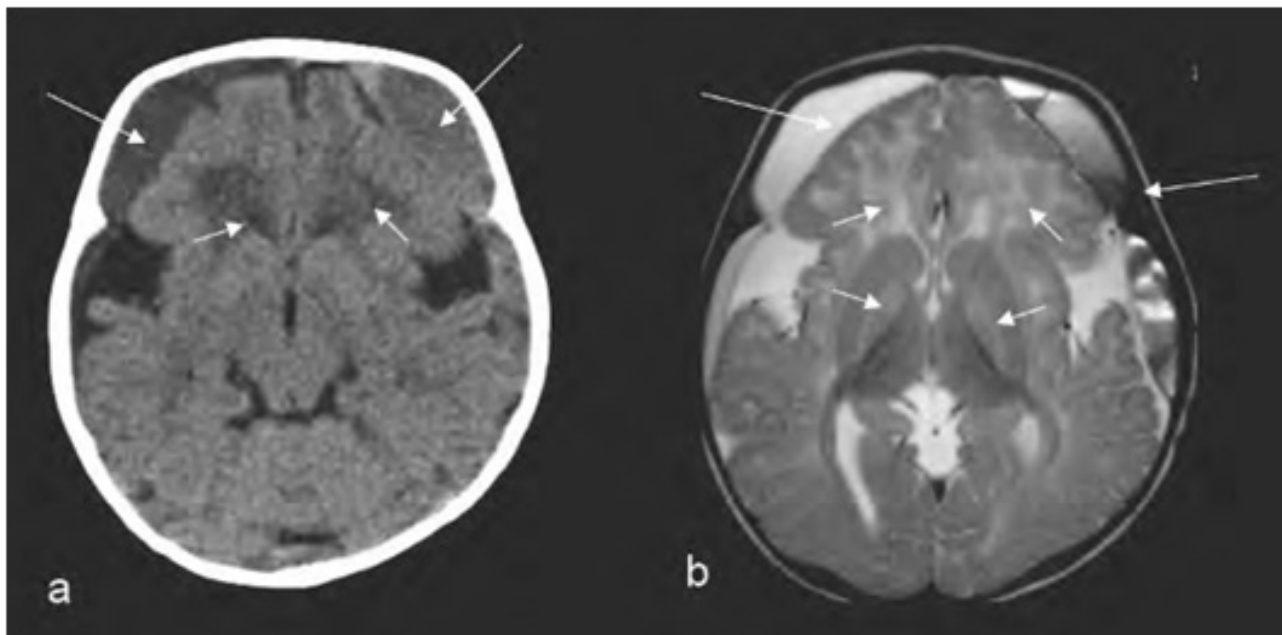


Figure 11 CT (a) and T2 MRI (b) of a 12 month-old infant showing bilateral SDH (long arrows) and basal ganglia and cerebral white matter abnormalities (short arrows) from glutaric aciduria type I^[11].

most commonly^[16]. If these different indicators are insufficient to differentiate the two problems, a “biochemical analysis of cultured skin fibroblasts is diagnostic in approximately 85 percent of patients with the disease”^[20, p1827].

Copper deficiency

Copper deficiency can cause abnormal skeletal radiology presenting as apparent fractures^[13]. However, there are many signs and symptoms caused by copper deficiency that are not shared with NAI. This includes low copper stores, anaemia, neutropenia, psychomotor retardation, osteoporosis and hypotonia^[13]. These signs should be considered carefully by the clinician before reaching a final diagnosis.

Coagulopathy

Intra-cranial haemorrhages may be caused non-abusively by haemophilia or vitamin K deficiency leading to hypoprothrombinaemia^[20]. Blood tests to analyse platelet count, prothrombin time, partial-thromboplastin time and bleeding time should assist inclusion or exclusion of coagulopathies in the differential diagnosis^[20].

Metabolic disorders

Glutaric aciduria type I can cause SDH and cerebral atrophy^[20]. However, skeletal injuries and retinal haemorrhages are not associated with the disorder^[20]. If this is somehow insufficient, urinary screening will confirm any suspicions^[20]. Figure 11 presents an alleged NAI showing highly indicative SDHs of various ages suggesting repeated cases of abuse. However, the patient was later confirmed to have glutaric aciduria type I^[11]. Additionally, Menke’s disease is a rare congenital metabolic disorder causing metaphyseal hooks which may present as ‘corner’ fractures^[5,7].

Other mimics

Other radiological impersonators include: vascular diseases, infectious and post-infectious conditions, venous thrombosis, neoplastic diseases, some therapies, extracorporeal membrane oxygenation and congenital and dysplastic disorders^[5,7].

CONCLUSION

Radiology is key to effective management of child abuse cases. Radiological findings of highly indicative features of NAI can be pivotal to early clinical detection of child abuse leading to appropriate child health and social care management. No radiological finding is pathognomonic of NAI alone and must be considered with other findings and, crucially, appreciated with an inconsistent or inappropriate history of events, in a multi-disciplinary setting. The selection of appropriate imaging modalities and techniques is essential for effective detection of potential NAI for efficient medical intervention. The radiologist must be adequately trained for these sensitive cases and is supported by national clinical radiological standards for guidance. Radiologists are often the first to detect and suggest NAI diagnosis and will play a key role in legal cases for evidence of child abuse^[2,13]. The failure to miss NAI in a differential diagnosis or, conversely, incorrectly reach a NAI misdiagnosis can have massive implications. This highlights the importance of accurate radiological detection of NAI from possible mimics. Further research could go into exploring suspected mechanisms of SBS and other biomechanical factors in NAI, which would assist radiological evaluation and clinical diagnosis. Effective communication in the multidisciplinary team between radiologists and other clinicians from the foundation of the radiology report will significantly improve the diagnosis of NAI. This can be the difference between efficient and appropriate management of child abuse cases and the unlawful and tragic break-up of a family.

CONFLICT OF INTEREST

There are no conflicts of interest with regard to the present study.

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