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SPECIAL ISSUE: ABUSIVE HEAD TRAUMA

Imaging abusive head trauma: why use both computed tomography and magnetic resonance imaging?

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Abstract Abusive head trauma is the leading cause of death in child abuse cases. The majority of victims are infants younger than 1 year old, with the average age between 3 and 8 months, although these injuries can be seen in children up to 5 years old. Many victims have a history of previous abuse and the diagnosis is frequently delayed. Neuroimaging is often crucial for establishing the diagnosis of abusive head trauma as it detects occult injury in 37% of cases. Several imaging patterns are considered to be particularly associated with abusive head trauma. The presence of subdural hematoma, especially in multiple locations, such as the interhemispheric region, over the convexity and in the posterior fossa, is significantly associated with abusive head trauma. Although CT is the recommended first-line imaging modality for suspected abusive head trauma, early MRI is increasingly used alongside CT because it provides a better estimation of shear injuries, hypoxic-ischemic insult and the timing of lesions. This article presents a review of the use and clinical indications of the most pertinent neuroimaging modalities for the diagnosis of abusive head trauma, emphasizing the newer and more sensitive techniques that may be useful to better characterize the nature and evolution of the injury.

Keywords Abusive head trauma · Child abuse · Head injury · MRI · CT

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Introduction

The World Health Organization (WHO) defines child maltreatment as "all forms of physical and/or emotional ill-treatment, sexual abuse, neglect or negligent treatment or commercial or other exploitation, resulting in actual or potential harm to the child's health, survival, development or dignity" [1].

Abusive head trauma includes inflicted cranial, cerebral and spinal injuries resulting from blunt force trauma, shaking or a combination of forces [2]. It is the most serious form of physical child abuse with an associated mortality of 30% and morbidity in 50% of survivors [2–4].

In 1946, John Caffey [5] observed and published case reports of infants with chronic subdural hematoma who presented with enlarged head, bulging fontanel and neurological symptoms, with associated fractures and contusions of the long bones, some more acute than the chronic subdural hematomas. Posteriorly, in 1974, he linked violent manual shaking of an infant to brain damage, ocular hemorrhages and residual mental retardation, emphasizing the lack of external evidence of abuse [6].

In the child who has experienced non-accidental injury, abusive head trauma is the most common cause of fatality and long-term morbidity. Ninety-five percent of serious central nervous system (CNS) injuries occurring in infants younger than 1 year old are attributed to abusive head trauma. Up to 80% of fatal child abuse injuries are attributed to head injury [7].

The reported incidence of abusive head trauma in children is similar in the United States and Europe, with rates of 25 and 29 per 100,000 person-years, respectively, in the first year of life of [8, 9]. A history or clinical evidence of previous maltreatment is noted in 60% of children with abusive head trauma [10]. Abused infants with head injuries frequently present with nonspecific clinical features and no history of trauma. Imaging evidence of brain injury may occur with or without other clinical findings of trauma (e.g., bruises or burns) or other traditionally higher-specificity imaging findings of abuse (e.g., classic metaphyseal lesions or rib fractures) (Fig. 1). The initial clinical presentation of abusive head trauma can be highly variable and includes irritability, vomiting, apnea, seizures and obtundation. The history provided by parents or caregivers is often vague and changes with time. As a result, as many as 30% of children with inflicted head injuries may be misdiagnosed at the initial evaluation [10, 11], their condition being attributed to other diagnoses, such as viral gastroenteritis, influenza or accidental head injury. Up to 28% of children with missed abusive head trauma diagnoses may be reinjured leading to permanent neurological damage or even death [11]. On the other hand, when a false-positive diagnosis of abusive head trauma is made, parents or caregivers may be falsely accused of assault.

Imaging findings may be the first indicators of abuse in a child with an apparent natural illness; thus, imaging examinations play a crucial role in evaluating infants and children with inflicted head trauma. Children with both accidental and inflicted head trauma may present with different combinations of neuroimaging features, and each finding seen in abusive head trauma, when considered separately and without taking into account the clinical history, can also be the result of accidental head injury. Consultation with radiologists and neuroradiologists is critical in establishing an appropriate and accurate diagnosis. Hence, all radiologists should be highly familiar with the classic and unusual imaging patterns associated with inflicted injury to help recognize the cause of the child's condition.

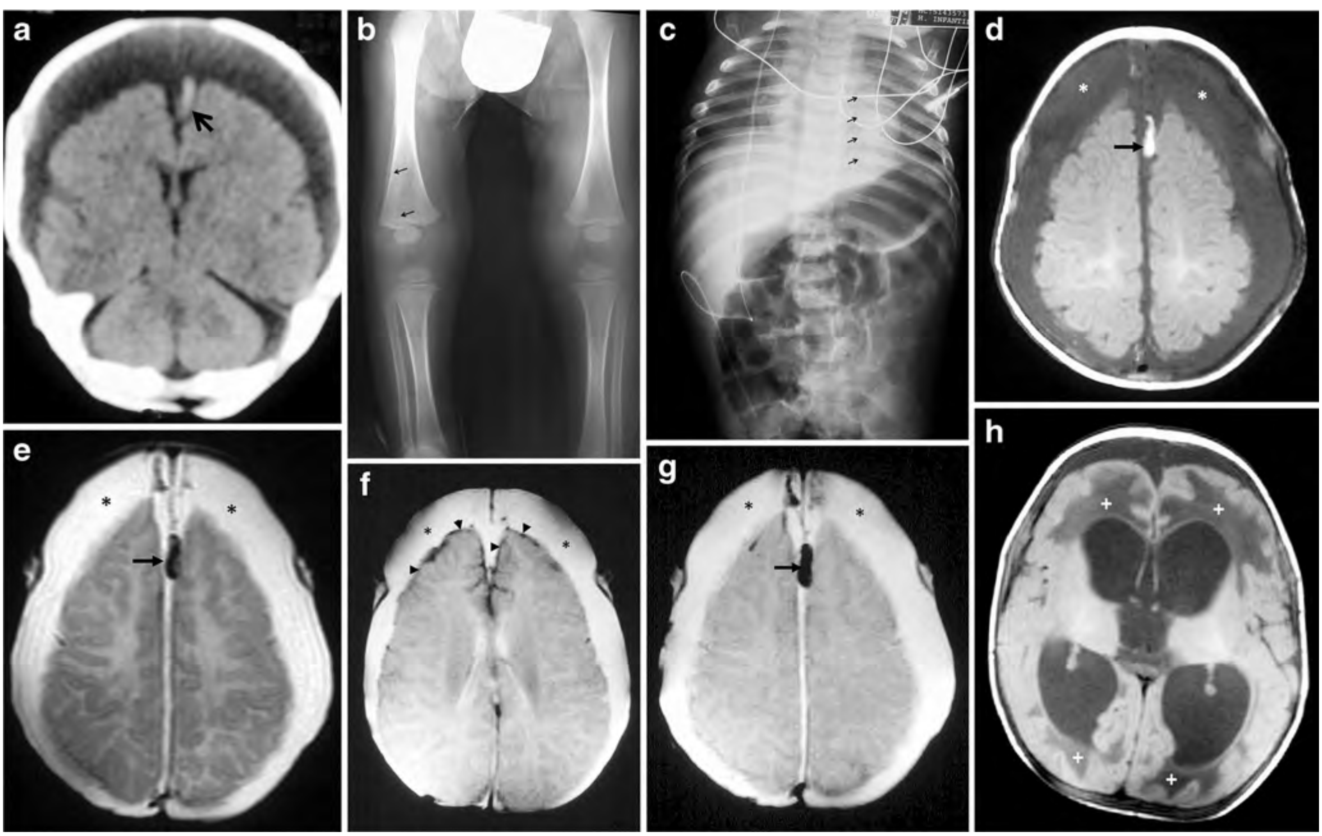


Fig. 1 Subdural hematoma in a 3-month-old abused girl with seizures. **a** Chronic hypodense bilateral subdural hematomas surrounding the brain and cerebellum are demonstrated on cranial CT. Note the presence of a hyperdense component within the interhemispheric area (*arrow*). **b** Skeletal survey disclosed fractures with different ages involving the right femur and (**c**) posterior ribs (*arrows*). MR imaging was after performed and showed the subdural collections (*asterisks*) on (**d**) axial T1-W, (**e**) T2-W and (**f**, **g**) gradient recalled echo (GRE) T2*-W images. In these, hemorrhagic deposition within the subdural collections is highlighted (*arrowheads*), as well as thrombosed veins (*arrows*). **h** Follow-up MRI disclosed severe hydrocephalus on axial T1-W, with transependymal edema (*plus signs*)

Mechanisms of injury

Specific injuries associated with abuse include subdural hemorrhage (typically diffuse, thin-layered, and often along the falx or over the bilateral cerebral convexities), diffuse multilayered retinal hemorrhages and diffuse brain injury (previously known as shaken baby syndrome). Mechanisms involving shaking with or without impact have been proposed to explain this pattern [3, 5, 6].

Several factors may increase the susceptibility of infants and young children to brain damage: movement of the brain with acceleration-deceleration forces is greater in an infant, the skull is thinner and more pliable, the infant's head is relatively large, heavy and unstable, and, finally, the developing brain is softer, has high water content and is undermyelinated [6, 12].

Direct injury resulting from traumatic rotational and translational forces is responsible for primary parenchymal injury, including traumatic axonal injury [13]. Secondary mechanisms of hypoxia-ischemia due to central apnea from injury to the brainstem or cervical spinal cord, prolonged seizure activity or aspiration occur three times more frequently in abusive head trauma than after serious unintentional head trauma [14].

Types of injury

Intracranial bleeding

Intracranial bleeding, including subdural hemorrhage, intraparenchymal bleeding, epidural hemorrhage, subarachnoid hemorrhage or a combination of all these, is one of the characteristic features of abusive head trauma.

Subdural hemorrhage is significantly associated with abusive head trauma, particularly cases with multiple hemorrhages showing differing attenuation on CT, an interhemispheric or posterior fossa location, or extension over the hemisphere convexity. Subdural hemorrhages may appear contracoup to the site of impact. Abused infants with head injury often present with chronic subdural collections with or without additional acute injuries, suggesting prior episodes of abuse [15]. The association of abusive head trauma with multiple subdural hematomas of differing attenuation has been interpreted as indicative of repetitive inflicted head injury (Fig. 1). However, it is now known that hemoglobin degradation, red blood cell hydration, integrity of cell membranes, protein content of the blood clot, sedimentation rate and concentration of red blood cells, and amount of cerebrospinal fluid within the collection are all factors that can affect the appearance of acute subdural collections [16, 17]. Presentation with an acute mixed–density subdural hematoma is more common in abusive than accidental trauma owing to coexistence of hyperacute and acute blood, early clot retraction, mixture of blood and CSF due to traumatic arachnoid tear, and presence of both acute and chronic hematomas [18]. CT and MRI findings are complementary when it comes to dating an injury and characterizing intracranial hemorrhage [19]. In fact, MRI is more sensitive than CT in the identification of membranes within the subdural collection, and presence of these membranes is a very useful indicator for old hemorrhage [18] (Fig. 2).

Epidural hemorrhage occurs significantly more often following unintentional head trauma than abusive trauma. It usually results from a fall, which produces a typically small

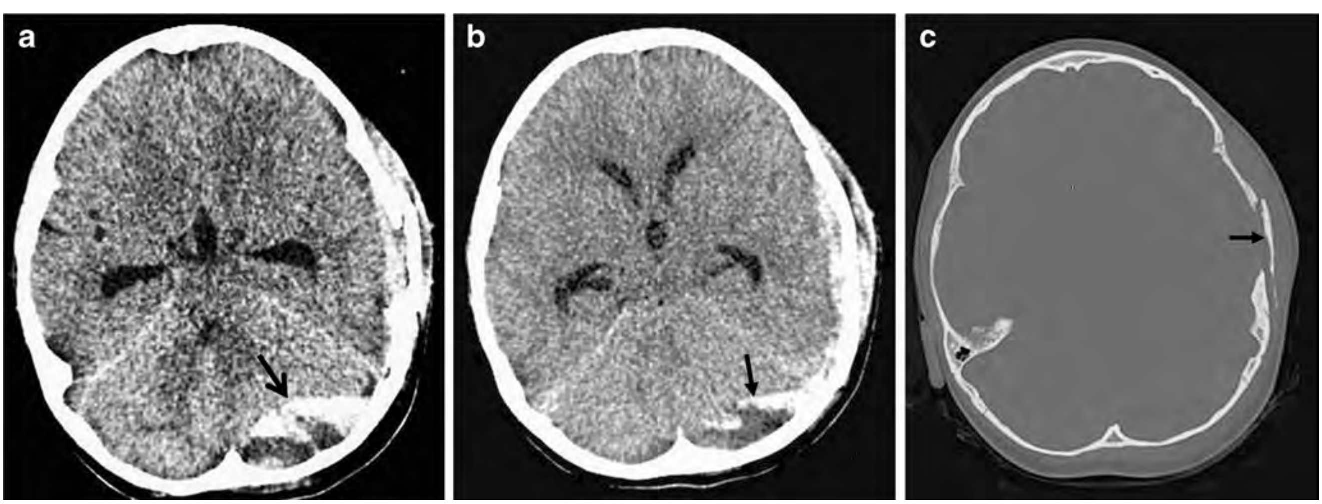


Fig. 2 Mixed density acute subdural hemorrhage in the posterior fossa in a 18-month-old girl. **a, b** Axial CT image demonstrates a heterogeneous posterior fossa collection (*arrows*), together with a left hyperdense temporal hematoma, both being of acute origin, as well as (**c**) a displaced temporal fracture (*arrow*)

hemorrhage without other associated injuries, except for retinal hemorrhages [20].

Subarachnoid hemorrhage is present in nearly all fatal cases of inflicted head trauma, but it does not occur more commonly after inflicted head trauma than following unintentional head trauma [21, 22].

Retinal hemorrhages are common in children with abusive head trauma, (present at ophthalmoscopy in approximately 80–92% of cases), but they occur much less often in unintentional head injury [23]. When associated with abusive head trauma, retinal hemorrhages are characteristically numerous, involve multiple layers of the retina, and extend beyond the posterior pole to the peripheral retina (Fig. 3). They may also be visible on MR imaging. Although retinal hemorrhages can also occur in children with non-abusive traumatic brain injury, they are seen in less than 10% of cases and are generally limited to the posterior pole and to a single layer of the retina [24, 25].

Parenchymal injuries

These result from contact forces, inertial forces and overall hypoxia/ischemia. Contact forces may cause cerebral contusion and laceration. Inertial forces may lead to focal or diffuse axonal injury, commonly involving the subcortical white matter, corpus callosum, periventricular regions and dorsolateral aspect of the rostral brainstem [12, 21, 22]. Intra-axial cerebral hemorrhage is often associated with diffuse axonal shearing injury and is often located at the gray/white matter interface or in white matter tracts, such as the corpus callosum. Hypoxia-ischemia resulting from apnea, respiratory distress, secondary hypotension or prolonged seizure activity often occurs in children with abusive head trauma and is an important contributor to a poor outcome [21, 22]. Severe abusive head trauma may cause primary damage to the brainstem, including the respiratory centers (possibly from hyperflexion/hyperextension injury), which initiates widespread secondary hypoxia, leading to global hypoxic-anoxic changes and brain swelling [26]. A typical finding of global ischemia is the diffuse loss of gray-white matter differentiation with decreased attenuation in the cortex ("reversal sign"), with relative sparing of thalami, basal ganglia, cerebellum and brainstem, which therefore appear bright [27] (Fig. 4). More recent studies that include diffusion-weighted MRI provide confirmation of the association between hypoxia ischemia and abusive head trauma [28, 29]. Susceptibility-weighted imaging (SWI) is a volumetric three-dimensional gradient-echo imaging technique that may be three to six times more sensitive than conventional T2*-weighted gradient-echo sequences in depicting hemorrhagic lesions in diffuse axonal injury and in detection of retinal hemorrhages in children with suspected abusive head trauma [30]. Subacute and chronic parenchymal changes of abusive head trauma include hydrocephalus, chronic subdural hematomas, cerebral gliosis, atrophy and impaired head growth [26, 31, 32].

Skull fractures

They are commonly seen in children with abusive head trauma, but they are also common in unintentional head injury. The probability of abuse in children with a skull fracture is estimated at 30% [33]. Linear parietal skull fractures are the most common type of skull injury (78%) following both unintentional and inflicted trauma. Abusive injury should be suspected when the history is inconsistent with the physical examination findings (Fig. 5). Bilateral fractures, multiple fractures, depressed fractures, fractures with diastases >3 mm of the fracture lines and occipital fractures are more commonly seen in child abuse, although the specificity of complex skull fractures as indicators of child abuse varies between the related studies [34].

Spinal injuries

They are an additional well-documented feature of abusive head trauma. They include direct spinal cord injuries, nerve

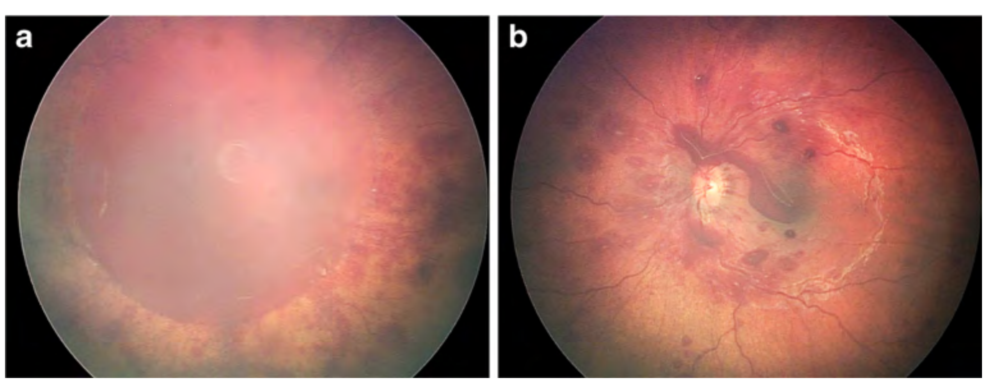


Fig. 3 Retinal hemorrhages in abusive head trauma in a 7-month-old boy. **a** Right eye. **b**. Left eye. Several characteristic hemorrhages are seen involving multiple layers of the retina and extending beyond the posterior pole to the peripheral retina

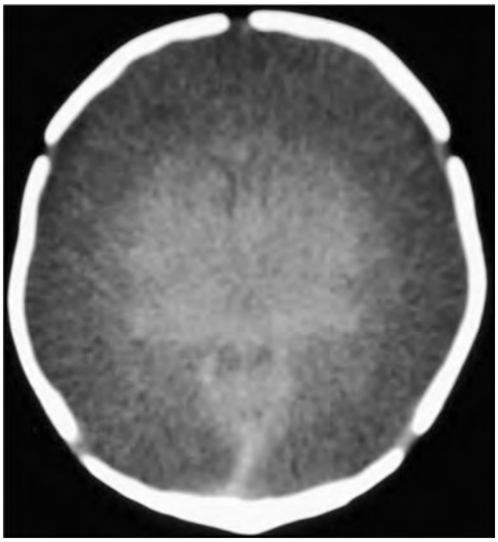


Fig. 4 Parenchymal injury in abusive head trauma in a 6-month-old girl. Reversal sign on CT. Unenhanced axial CT image reveals inversion of the normal attenuation relationship between gray and white matter whereas density of the thalami is increased. This is associated with a poor prognosis and indicates irreversible brain damage

root injuries or avulsions, epidural and subdural hemorrhages, spinal ligamentous injuries, bone edema and fractures. A recent study reported the presence of intraspinal subdural hemorrhage in more than 60% of children with abusive head trauma in whom thoracolumbar imaging was performed (Fig. 6), whereas this feature was rare in accidental trauma [33]. Several authors consider it important to include complete spinal imaging in all children undergoing brain MRI for moderate or severe abusive head trauma [32, 35, 36].

Neuroimaging approach

Several imaging tools, including plain skull radiography, US and, particularly, CT and MRI may be used in the diverse institutions that deal with children with suspected abusive head trauma. Imaging should be directed toward establishing the correct diagnosis as soon as possible to prevent potentially catastrophic consequences. Several organizations and reports have published guidelines on the indications for neuroimaging of suspected abusive head trauma [31, 37–40]. Neuroimaging techniques should clarify whether the child has had a

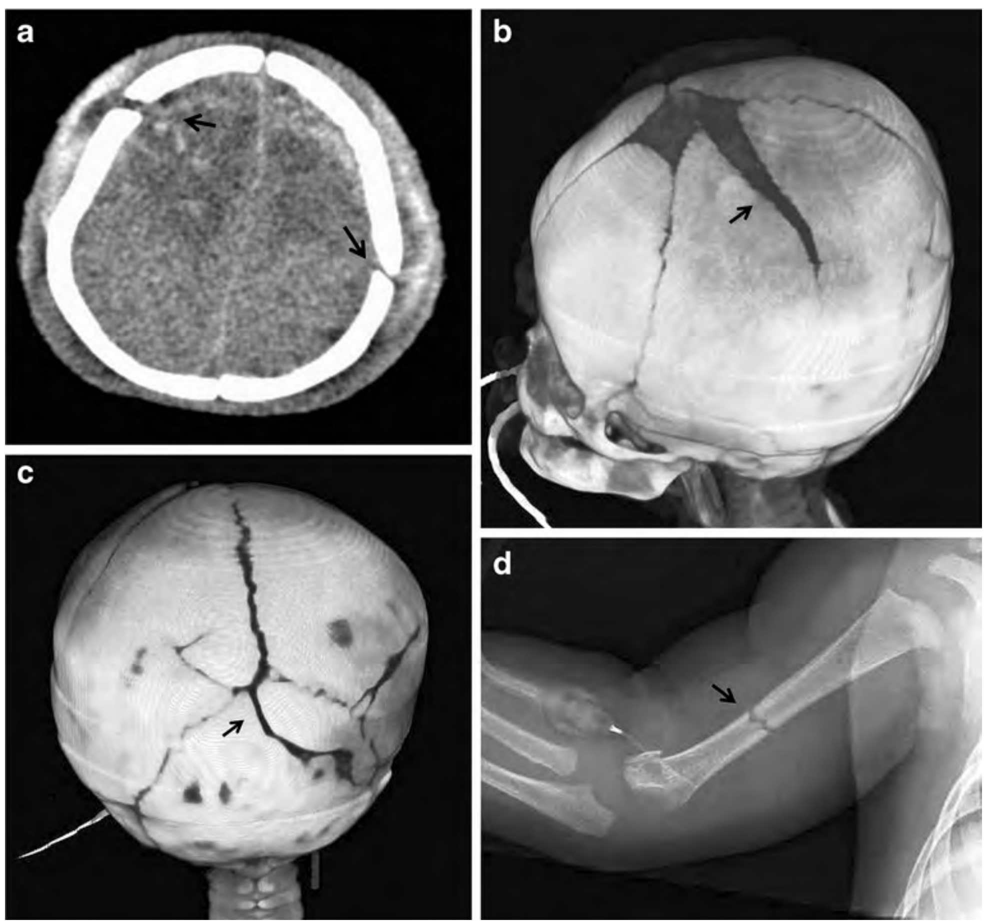
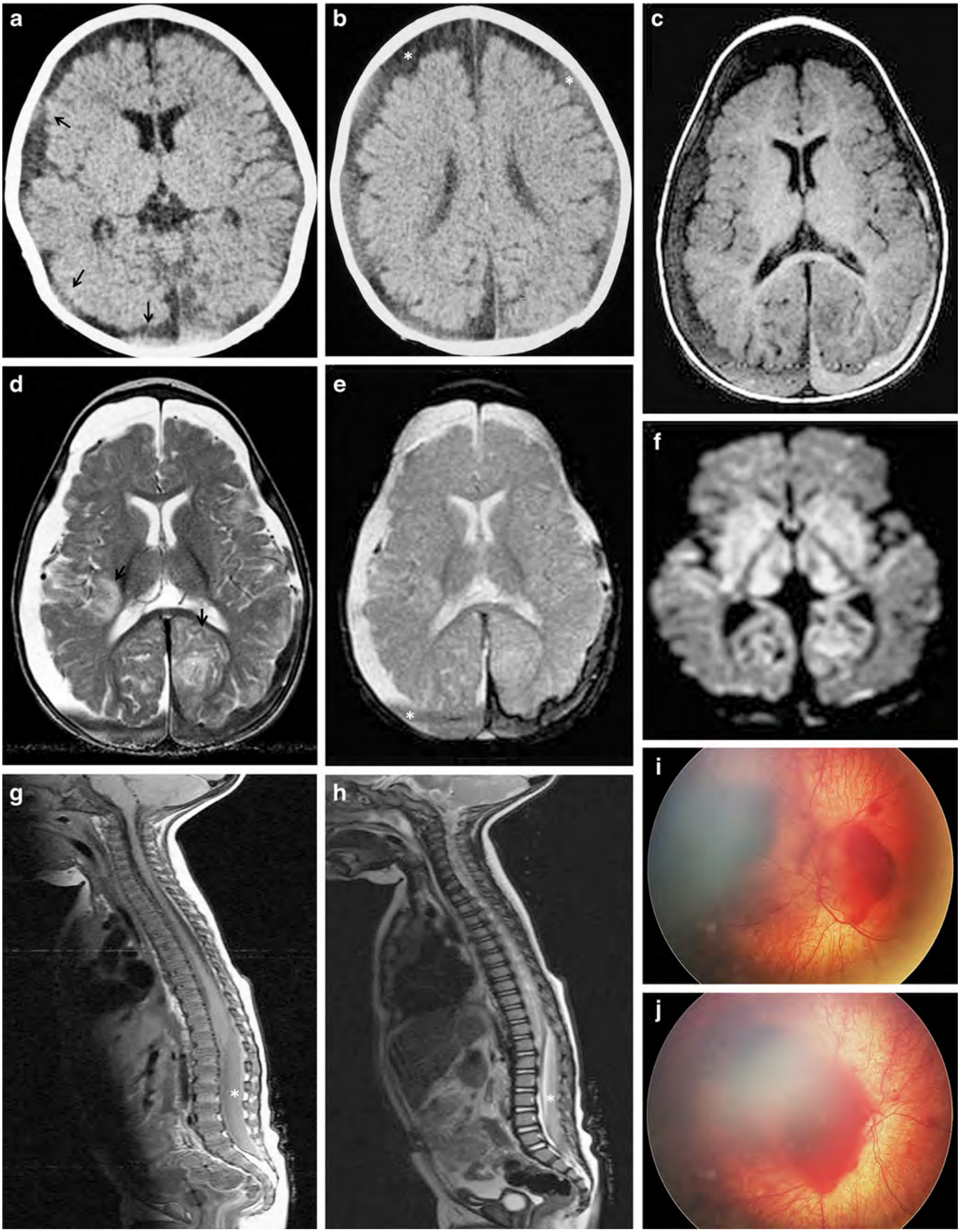


Fig. 5 Parenchymal injury and skull fractures in a 3-month-old boy suspected of suffering abusive head trauma. **a** Axial CT demonstrates hemorrhagic contusions in both cerebral hemispheres with diastatic skull fractures (*arrows*) and extracranial soft-tissue injury. **b**, **c** Surface rendered 3-D CT images clearly show the complexity and extent of the fractures (*arrows*). **d** Fractures involving the right humerus were also discovered in the skeletal survey (*arrow*)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◀ **Fig. 6** Intraspinal subdural hemorrhage in a 6-month-old boy with suspected shaken baby syndrome. **a, b** Axial non-contrast CT image obtained on admission show bilateral hypodense effusions (*asterisks*) with some hyperdense components (*arrows*). There is also diminished gray-white matter differentiation. **c** Early MRI was performed and revealed subdural collections with different signal characteristics on T1-W and (**d**) parenchymal signal abnormalities on T2-W (*arrows*). **e** The hematic components within the subdural collections are better demonstrated on axial gradient recalled echo (GRE) T2-W image, as well as fluid/fluid level (*asterisk*). **f** Diffusion-weighted imaging shows deep gray matter restriction indicating acute hypoxic-ischemic brain injury. **g**\ Sagittal T1 and (**h**) T2-W of the spinal region disclosed distal cord edema and a large subdural collection involving the lumbosacral spinal canal (*asterisk*). **i**, **j**. Fundoscopic examination revealed widespread bilateral retinal hemorrhages

traumatic injury, as well as the timing, severity, number of episodes and prognosis of that injury.

According to the American College of Radiology (ACR) recommendations, neuroimaging indications depend on the child's age and type of presentation. In children with skull fractures or clinical signs and symptoms of intracranial injury, an immediate non-contrast CT should be performed. If the CT does not detect significant lesions that require rapid neurosurgical intervention and the clinical presentation warrants further assessment, an MRI scan should be performed. In a child with an abnormal CT, additional assessment with MRI should be considered to further assess the extent of post-traumatic injury. In those children who are suspected abuse victims and show no objective evidence suggesting intracranial injury, MRI avoids the radiation of CT and is a particularly good choice [38]. Following the guides proposed by the Royal College of Radiologists (United Kingdom) and the Royal College of Paediatrics and Child Health (United Kingdom), neuroimaging should be undertaken in any child who presents with evidence of physical abuse with encephalopathical signs or focal neurological signs or hemorrhagic retinopathy, as well as any child under the age of 1 year where there is physical evidence of abuse [39].

Controversial information has been reported as to whether CT and MRI can differentiate between accidental and inflicted brain injury [15, 16, 41]. A recent review on the diagnostic value of CT and MRI in 367 children diagnosed as having abusive head trauma [42] reported additional information in 25% of cases when MRI was acquired after an abnormal early CT examination (subdural hematomas, subarachnoid hemorrhage, diffuse axonal injury and ischemia/infarction). MRI also helped demonstrate recurrent episodes of injury and in dating of parenchymal injuries, although dating the subdural hemorrhages may be imprecise even using both CT and MRI.

A *skull radiograph* is obtained to detect possible fractures that are missed on CT because of their location in the plane of scanning. Skull radiography, usually part of the skeletal survey, should include an anteroposterior and one lateral view. As skull fractures heal without callus formation, the accident cannot be dated based on radiographic skull findings, hence, plain films of the skull should be omitted in follow-up skeletal surveys [28].

Cranial ultrasound is not indicated as a diagnostic modality for the evaluation of abusive head trauma due to the fact that it is only feasible in children younger than 6 months of age and often fails to detect thin convexity subdural collections or subtle parenchymal damage. It can, however, be used in some cases for follow-up of intracranial pathology [27]. Color Doppler US is usually the first modality used in children with increased cranial perimeter (Fig. 7). This technique can depict the bridging veins traversing the extra-axial spaces (positive cortical vein sign) that are typical in benign enlargement of the subarachnoid space (BESS), thus differentiating BESS from subdural hematoma [43]. Spontaneously occurring subdural hematomas are rare in infants with BESS (Fig. 8). Color Doppler US may be used only when the increased cranial perimeter is isolated without any other neurological symptoms, and progressive since the first weeks after birth, to avoid misinterpretation between BESS and old subdural hematoma. Even more, the presence of asymmetry, convexity, extra-axial fluid collections or extra-axial collections with complex fluid characteristics should be further investigated with MRI [44]. On CT, a hypoattenuating subdural hematoma may be misinterpreted as BESS, so this pattern should prompt clinicians to seek bruises or previously unexplained symptoms [3].

Advantages and disadvantages of CT

CT is widely accepted as the modality of first choice in an acutely ill child with neurological symptoms. Therefore, unenhanced CT of the head, a relatively accessible and fast technique, is usually the initial radiologic examination used in suspected abusive head trauma. CT can be performed quickly and safely in a child who is acutely ill and potentially unstable, without the need for special monitoring equipment [31]. CT is very sensitive in detecting skull fractures and acute blood, and is useful for identifying brain edema and ischemic changes.

The disadvantages of early cranial CT in the setting of suspected abusive head trauma are the radiation involved and the lack of sensitivity in detecting petechial hemorrhages, non-hemorrhagic strain, shear injury, ischemic edema and ligamentous injuries of the craniocervical junction [45].

CT scans should be performed with soft-tissue algorithm reconstructions at a slice thickness of 5 mm, and with bone algorithm reconstructions, a slice thickness of 2.5 mm. CT settings should be age-adjusted to reduce the radiation to a minimum. Standard 3-D reconstructions are highly advisable to provide insight into the relationship among fractures, which can be useful to explain possible trauma mechanisms to non-medical personnel.

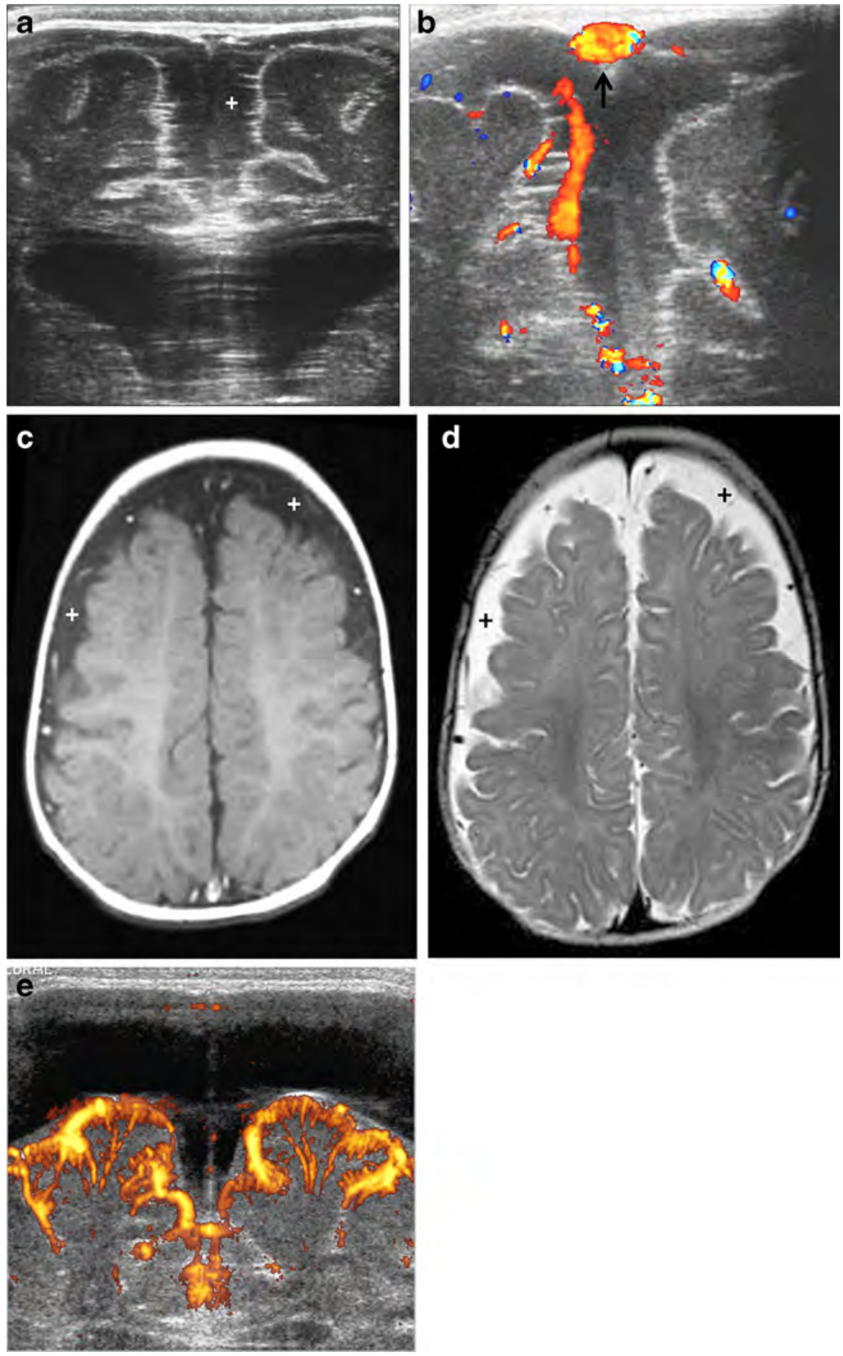

Fig. 7 Benign enlargement of the subarachnoid space (BESS) versus subdural collections on US in a 3-month-old boy. **a** Coronal US image demonstrates enlarged fluid space widening the interhemispheric fissure (*plus*). **b** Color Doppler shows the superficial cortical veins as they cross the enlarged subarachnoid space (positive cortical vein sign) toward the superior sagittal sinus (*arrow*). **c** Corresponding coronal MR T1-W and (**d**) T2-W images disclose the enlarged subarachnoid space (*plus signs*) without subdural collections. **e** Coronal US in another patient with subdural collections without crossing vessels being visible across the fluid collection

Cranial CT should be undertaken as soon as possible following admission [31, 32, 46]. CT images should be carefully examined, seeking skull fractures, intracranial hemorrhage, extra-axial fluid collections and loss of gray/white matter differentiation. The finding of a scalp swelling should be must be carefully looked for with bone or intermediate windowing, as it indicates an impact. Old fractures (without scalp swelling) may be difficult to differentiate from accessory fissures (normal variants). Subdural hemorrhage is seen on CT in 77% to 89% of abusive head trauma cases. CT is useful for raising the clinical suspicion or confirming the clinical diagnosis and may, in itself, predict a poor prognosis in terms of death or severe neurological sequelae in more critically ill patients [42]. In addition to standard assessment of axial CT data, rapid image reformatting (2-D maximum intensity projections [MIP] or 3-D surface-rendered reconstructions) of the original axial data should be performed in all patients with accidental or suspected abusive head trauma [45]. Although non-contrast brain CT is the preferred initial imaging exam for investigating abusive head trauma, there are occasions when supplemental contrast-enhanced brain CT imaging will prove useful; for example, to differentiate

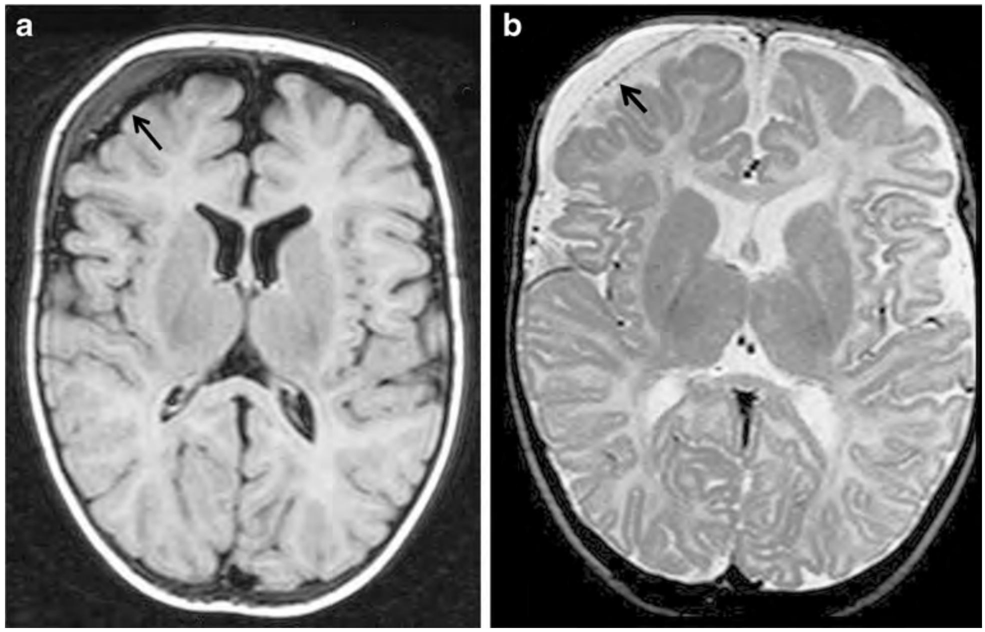

Fig. 8 Spontaneous development of subdural collection in BESS in a 4-month-old boy. MRI of the brain was performed owing to increasing macrocrania. **a** Axial FLAIR and (**b**) T2-W images show the extra-axial spaces mostly corresponding to subarachnoid space, but also with a small subdural component (*arrow*)

between subarachnoid or subdural collections, or to distinguish sinus venous thrombosis from intradural or subdural compartment collections [47]. Careful analysis of the vertex by CT or, even better, by MRI is strongly recommended to detect clots with a tubular shape, suggestive of acute bridging vein thromboses, considered as markers of acutely disrupted veins and having crucial diagnostic value [48].

Deduction of the injury chronology from CT exams may be difficult in abusive head trauma. Moreover, many concepts have changed over the last 2 decades: brain hypoattenuation such as the "reversal sign" (cerebral hemispheres appearing more hypodense than either deep nuclei or posterior fossa structures on CT) may appear earlier than was previously reported (within hours after injury), chronic subdural hematoma may also appear before the 1- to 4-week period, and mixed-attenuation subdural hematomas do not always reflect repeated episodes of trauma [49]. Nevertheless, demonstration of "age-different" lesions not only provides a strong argument for the diagnosis of abuse (Fig. 9), but also suggests repetitive violence and a high risk for further injury and death, unless protective legal action is undertaken [46].

Advantages and disadvantages of MRI

MRI is not the first imaging tool in suspected abusive head trauma because it has lower sensitivity for acute hemorrhage than CT and is more difficult to perform, owing to the length of the procedure, sensitivity to patient motion, and need for sedation and compatible monitoring equipment [28]. Nonetheless, additional use of MRI reveals new information in at least 25% of all children with abnormalities on the initial CT scan [17].

Brain MRI should be performed in all children with extracranial manifestations of abuse, those suspected of having inflicted head trauma with abnormal CT examinations, and those suspected of having been abused with encephalopathy and focal neurological signs, regardless of the CT findings [45]. When neurological signs are absent, MRI should be preferred to CT because of its higher sensitivity to detect parenchymal injuries or scars of different ages. In general, MRI is reserved for the stable patient, and is delayed 3 to 5 days following the acute injury. MRI examinations should be acquired with a standard pediatric brain protocol, which should include T1-weighted spin-echo images in different planes, T2-weighted images, FLAIR images, gradient-echo images and diffusion-weighted images. FLAIR imaging can be helpful for detecting subarachnoid hemorrhage, cerebral edema, contusions (coup and countercoup), shearing injuries (diffuse axonal injury), parenchymal lacerations and small subdural hematomas adjacent to the subarachnoid space [49]. FLAIR sequences are usually not mandatory in infants younger than 1–2 years old, owing to the poor brain myelination, and although they may be helpful to distinguish the different layers of subdural hemorrhages should not be used for any dating. MR images should therefore be examined for features of intracranial hemorrhage, extra-axial fluid collections, blood of different ages, restricted diffusion and edema.

Gradient recall echo (GRE) imaging and susceptibility-weighted imaging (SWI) techniques are sensitive for detecting the oxidation products of hemoglobin and are valuable for identifying older shear injuries and small petechial hemorrhages. In particular, SWI depicts 4–6 times as many

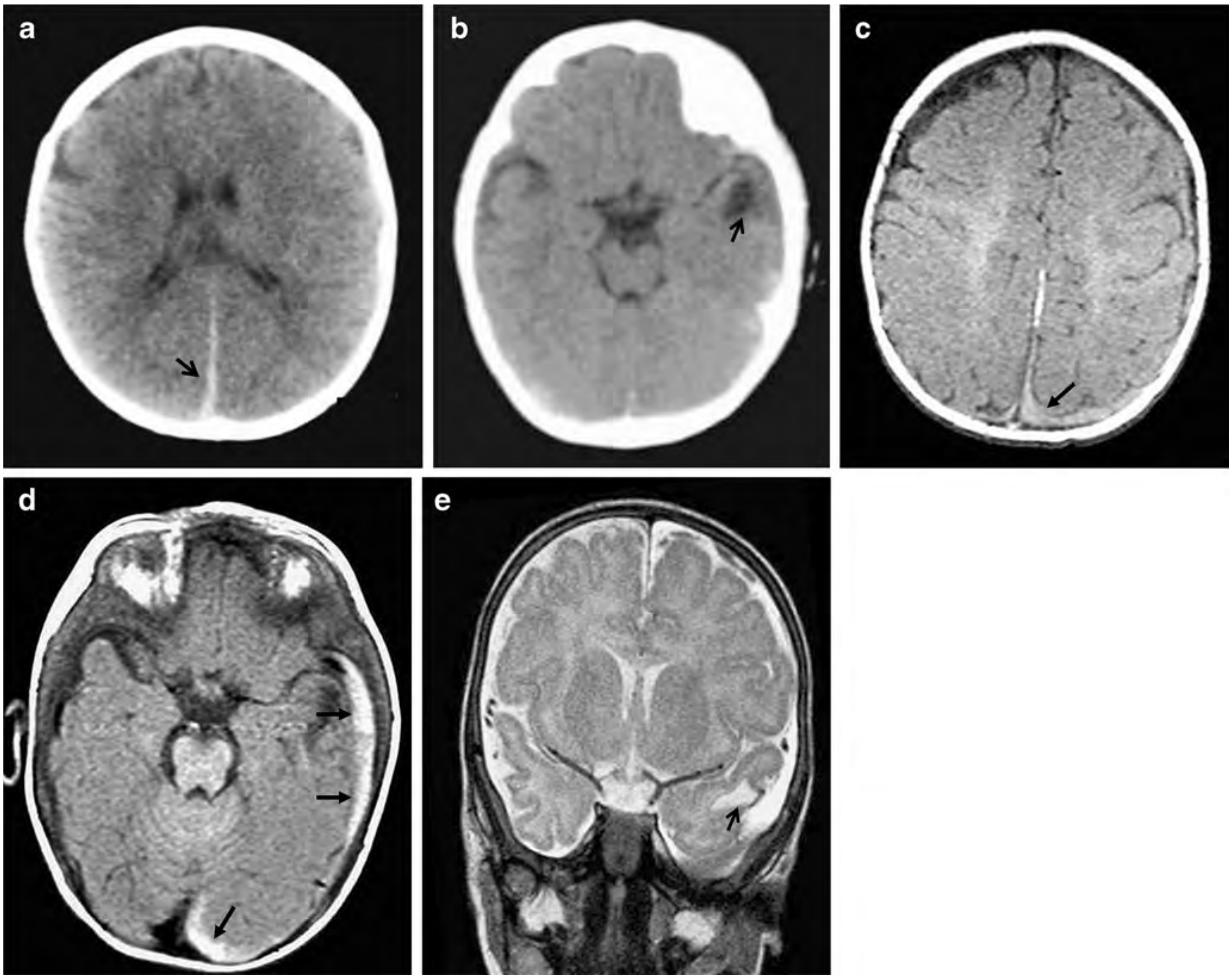

Fig. 9 Age-different lesions in a 5-month-old boy with status epilepticus. Axial CT images showed (**a**) posterior parafalcine subdural hemorrhage (*arrow*) and (**b**) a left temporal old lesion (*arrow*). **c**–**e** MR axial T1-W image disclosed (**c**) the subdural interhemispheric (*arrow*), and (**d**) left convexity subdural hematomas (*arrows*), together with the intraparenchymal temporal lobe lesion. **e** Coronal T2-W better shows the cystic porencephalic lesion with hemorrhagic remnants (*arrow*)

microhemorrhages compared to standard T2 * GRE imaging in children with accidental trauma [30], and can also accurately predict long-term neurological and neuropsychological outcome (Fig. 10); the extent and number of microhemorrhages detected with SWI have been shown to correlate with a poor long-term outcome in children with abusive head trauma [50].

Diffusion-weighted imaging (DWI) is a technique to evaluate the differences in the rates of diffusion of water molecules in the brain. Moreover, hypoxia and ischemia due to reactive vasospasm, strangulation, cervicomedullary injuries or apnea are common mechanisms of intraparenchymal injury in children with abusive head trauma [14, 29]. Restricted diffusion reflects cytotoxic edema whereas facilitated diffusion occurs with vasogenic edema. Lesions with restricted diffusion are more common in the posterior watershed territories, a distribution that is considered more typical of abusive than accidental trauma. A recent study categorized the findings in DWI into five imaging patterns: diffuse supratentorial brain swelling, watershed infarction, venous infarction, diffuse axonal injury and contusion [29]. Other reports established that hypoxia-ischemia was more common in children with abusive head trauma who more commonly manifested seizures, needed intubation at presentation and required neurosurgical intervention [14]. The presence of areas of restricted diffusion indicating cytotoxic edema confirm the neuropathological observations that the parenchymal brain damage in abusive head trauma is predominantly due to diffuse hypoxic-ischemic encephalopathy and not to diffuse axonal injury. DWI is therefore helpful for assessing the presence and extent of early ischemic injury, as well as foci of diffuse axonal injury (Fig. 11). In addition, diffusion information routinely helps in dating the injury and in prognosticating patient outcome [28, 50–52]. The presence of microhemorrhages combined with evidence of ischemia on DWI, provided the highest

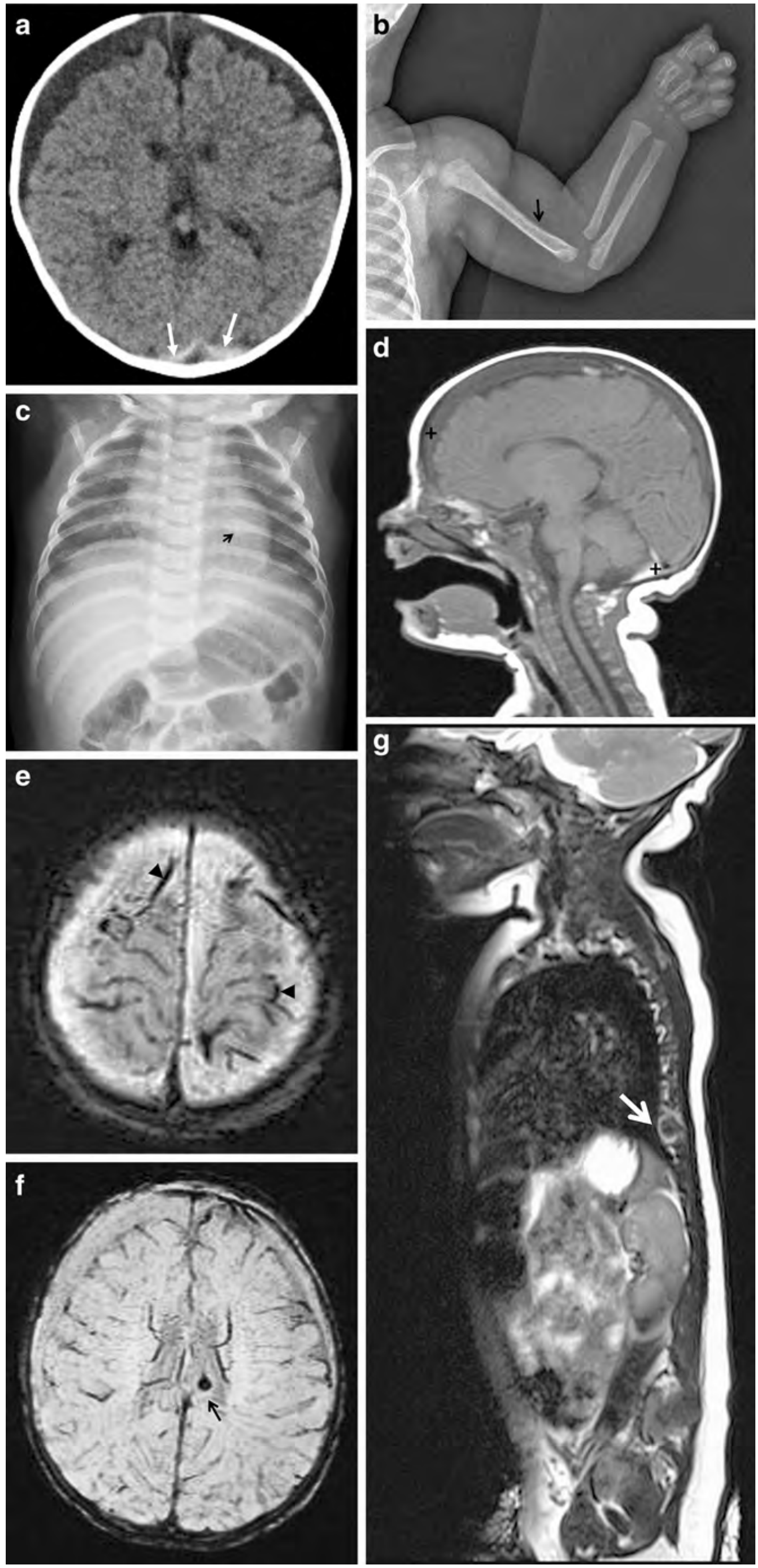

Fig. 10 Additional value of susceptibility-weighted imaging (SWI) in a 3-month-old boy with abusive head trauma. **a** Axial CT image shows bilateral pericerebral hypodense collections with posterior acute subdural hemorrhage (*arrows*). The skeletal survey disclosed a (**b**) suspected periosteal reaction in the left humeral diaphysis (*arrow*), and (**c**) a left sixth posterior rib fracture (*arrow*). **d**–**g** A MRI was performed afterward disclosing (**d**) subdural collections of different ages involving both supra- and infratentorial compartments on sagittal T1-W image, with subacute hyperintense component in the posterior fossa (*plus signs*). **e** Several subdural and subarachnoid hemorrhagic deposits can be seen on SWI, some of them with a tubular shape (*arrowheads*) probably corresponding to venous thrombosis. **f** A hemorrhagic lesion could also be revealed involving the posterior corpus callosum on SWI (*arrow*) suggestive of diffuse axonal injury. **g** Spinal MRI did not demonstrate abnormal findings, but the old rib fracture suspected on plain film was well depicted (*arrow*)

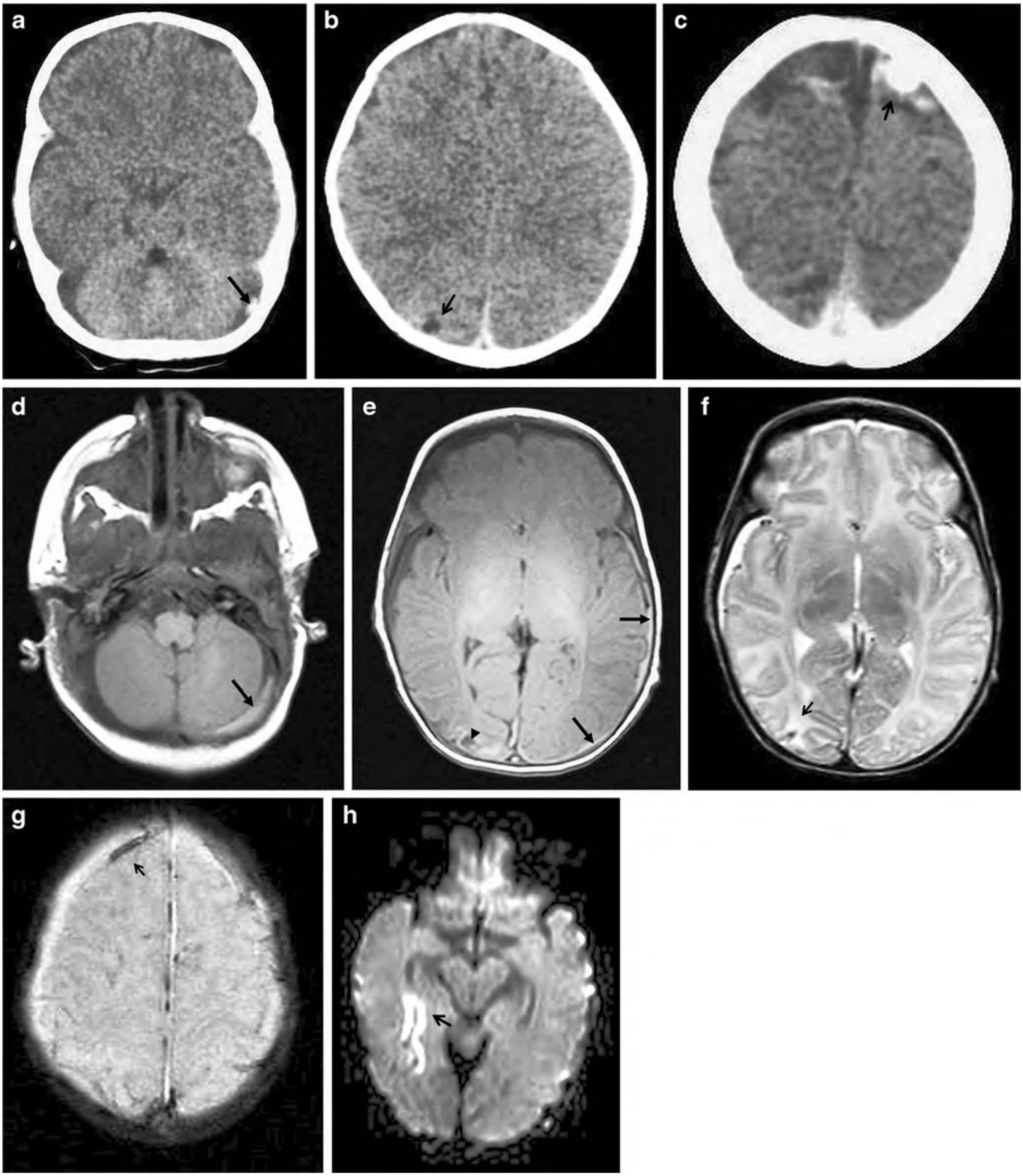

Fig. 11 Additional value of DWI in a 7-week-old boy with abusive head trauma. The patient had an antecedent of previous gastric perforation and was admitted with seizures and obtundation. **a**–**c** Axial CT images disclose (**a**) posterior fossa subdural collection suggesting several ages, with hypodense fluid as well as a hyperdense area (*arrow*), together with (**b**) a right parietal chronic parenchymal lesion (*arrow*), and (**c**) areas of hyperdensity near the vertex (*arrow*), representing recent subdural hemorrhage or acute disrupted bridging veins. **d**–**h** Later MRI displays the (**d**) pericerebellar fluid collection (*arrow*), and (**e**) a small left pericerebral subdural hematoma (*arrows*), and (**e**, **f**) a right occipital cortical tear (*arrowhead* in **e**, *arrow* in **f**), as well as (**g**) hemorrhagic deposits on gradient recalled echo (GRE) T2* (*arrow*) and (**h**) restricted diffusion in the right temporal lobe (*arrow*)

predictive accuracy in a recent report [52], while other radiologic findings (e.g., extra-axial hemorrhages, skull or skeletal fractures) did not improve outcome prediction.

Diffusion tensor imaging is a form of DWI that allows better evaluation of white matter fiber tracts by taking advantage of the intrinsic directionality (anisotropy) of water diffusion in the human brain. It has been shown to be useful in identifying white matter abnormalities after diffuse axonal injury (DAI) when conventional imaging appears normal [52]. Vascular complications, including stroke and vessel dissection, are also better seen with magnetic resonance angiography and venography. MR venography performed following intravenous contrast can detect thrombi in superficial and central venous structures [28, 45, 48].

Magnetic resonance spectroscopy (MRS) has demonstrated reductions in NAA ratios and increased Cho/Cr suggesting DAI in normal-appearing brain in children with accidental trauma. Also in the context of abusive head trauma metabolite changes have shown to be more predictive of outcome than other clinical and MRI findings. Lactate is considered a marker for hypoxic-ischemic injury and its presence along with NAA/Cr ratios in abusive head trauma victims correlates with a poor prognosis [52].

Another important contribution of MRI is in the evaluation of the craniovertebral junction with detection of atlanto-axial separation, ligamentous injury, vertebral body compression, and epidural and intradural hemorrhages [35]. It is recommended to include craniocervical junction and spine imaging at the time of brain MRI in cases of suspected abusive head trauma, using T2- and T2-weighted fat-suppressed sequences, such as short tau inversion recovery (STIR), which improve detection of bone, ligament and adjacent soft-tissue edema [53]. MRI is reported to be helpful in detecting additional findings in patients whose outcome involves mild to moderate developmental delay [54].

Follow-up neuroimaging in abusive head trauma

There is no evidence-based approach for the follow-up of abusive head trauma. Repeated CT and MRI are both currently used, but the literature is inconclusive. Secondary injuries should be evaluated 7 to 10 days after the acute injury with repeated CT or (better) MRI, seeking hemorrhagic laminar cortical necrosis, enlargement of subdural collections and early development of hydrocephalus [30, 31]. In addition, MRI should be repeated 2 to 4 months after the initial injury to better evaluate the extent of end-damage for the prognosis and medicolegal information. This is helpful in predicting the level of neurodisability and future support that will be required for the abused children. It is very important to keep in mind is that normal neuroimaging doesn't rule out the possibility of sequelae in this setting, which is of relevance in the scope of medicolegal proceedings. A dedicated more extensive review for long-term follow-up is available in the same issue.

Differential diagnosis in abusive head trauma

There are mimics of non-accidental injury that often present as acute life-threatening events. These medical mimics include hypoxia-ischemia (e.g., apnea, choking, or respiratory or cardiac arrest), ischemic injury (e.g., arterial vs. venous occlusive disease), vascular anomalies (e.g., arteriovenous malformation), seizures, infectious or postinfectious conditions, coagulopathies, and metabolic or connective tissue disorders, including vitamin deficiencies and depletions [55]. Neuroimaging is an important element in the differential diagnosis process of multiple other conditions that can mimic abusive head trauma, such as glutaric aciduria type 1 (Fig. 12),

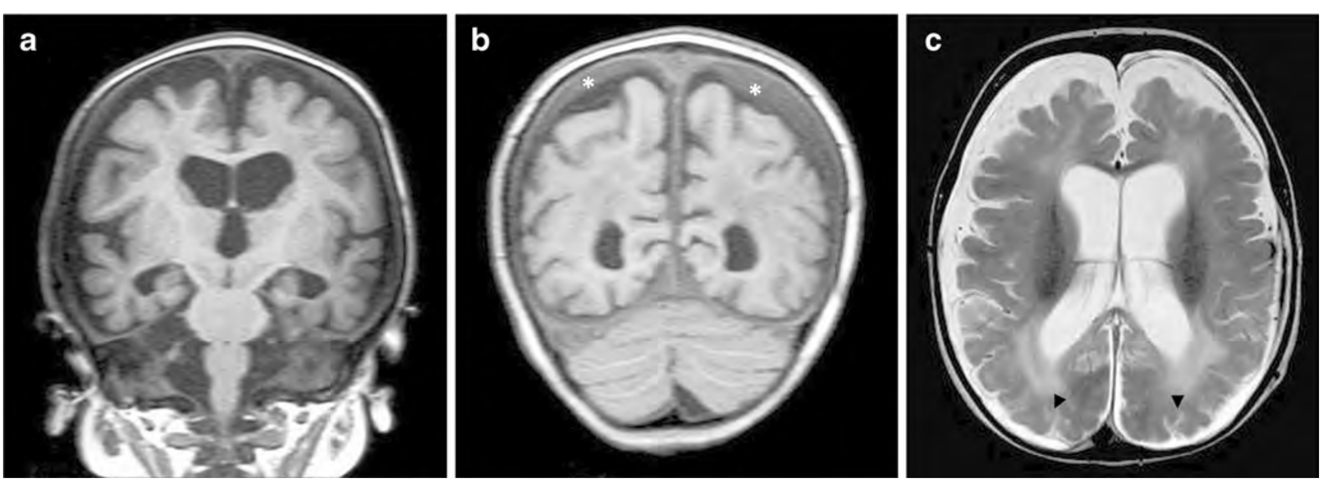

Fig. 12 Differential diagnosis in abusive head trauma. A 8-month-old boy with glutaric aciduria type 1. **a** Coronal T1-W image shows enlarged subarachnoid space and (**b**) small bilateral subdural collections (*asterisks*). **c** Axial T2-W image better demonstrates the ventricular enlargement as well as the abnormal hyperintense signal involving the white matter, mainly in the occipital areas (*arrowheads*)

galactosemia, homocystinuria, osteogenesis imperfecta, Menkes kinky hair syndrome or Alagille syndrome [56].

Conclusion

Abusive head trauma is an important cause of morbidity and mortality in infants and young children. Neuroimaging has become essential in establishing the appropriate diagnosis. Cranial CT and MRI provide complimentary information. CT is the initial method of choice for the work-up of suspected child abuse and is useful for predicting a poor prognosis in patients with severe neurological injury. MRI should be performed as an adjunct to CT, being particularly useful in detecting blood products of different ages, small areas of ischemia and diffuse axonal injury. MRI with DWI and SWI can provide complementary information and detect injury in brain regions that appear normal by conventional MRI, further increasing the diagnostic certainty and supplying additional prognostic information in children with less severe injuries. Nevertheless, the final diagnosis of abusive head trauma can never be based on radiologic findings alone; it should always be made by multidisciplinary team approach, involving pediatricians, radiologists, neurologists, ophthalmologists, nurses and social workers.

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Conflicts of interest None

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