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SPECIAL ISSUE: ABUSIVE HEAD TRAUMA

Dating the abusive head trauma episode and perpetrator statements: key points for imaging

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Abstract Shaken baby syndrome/abusive head trauma is a leading cause of morbidity and mortality in infants. The presence of a diffuse subdural hematoma without evidence of accident is a key diagnostic clue. The hematoma is typically attributed to rupture of the cerebral bridging veins due to violent shaking, with or without impact. Dating the incident, however, remains controversial. The aim of this article is to review the most reliable features used for dating the incident, based on both legal statements by perpetrators and medical documentation. The key points are: 1) The high (yet likely underestimated) frequency of repeated shaking is around 50%, 2) Children do not behave normally immediately after shaking, and the time of onset of even mild symptoms appears to be the best clue for dating the incident and 3) Brain imaging provides strong indicators of “age-different” injuries but the ranges for dating the causal event are wide. The density pattern in a single subdural hematoma location provides no reliable clues for assessing repeated violence. Only the finding of different density in two distant subdural hematomas argues in favor of “age-different” injuries, i.e. repeated violence. MRI is difficult to interpret in terms of dating subdural hemorrhages and must be analyzed in conjunction with CT. Most importantly, all of the child’s previous clinical and radiological data must be carefully studied and correlated to provide accurate information on the date and repetition of the trauma.

Keywords Subdural hematoma · Dating · Magnetic resonance imaging · Computed tomography · Abusive head trauma · Infant

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Introduction

Shaken baby syndrome – also known as abusive head trauma – is acknowledged as the most common cause of morbidity and mortality in infants. Diffuse subdural hematoma with no evidence of accident is a key diagnostic marker thought to be related to the tearing of the cerebral bridging veins due to violent shaking [1, 2]. Hypoxic-ischemic injuries are known to be frequently associated to the subdural hematoma and responsible for the outcome of the injured child [1, 2]. Dating the incident, however, remains very controversial as perpetrators rarely admit their actions.

The aim of this article is to review the most reliable features used for dating the incident, based on both a literature review including perpetrator admissions [3–5] and our own experience from a retrospective observational series, itself an extension of a previously published study [6].

From a cohort of 280 cases referred to 65 French courts for suspected SBS (2002–2013), we selected 66 cases for which detailed confessions – obtained during either police custody or forensic investigations – were available. Inclusion criteria were children younger than 4 years of age presenting with a subdural hematoma on computed tomography (CT) and perpetrator admission of a causal relationship between the violence inflicted and the child's symptoms. We analyzed all the written legal statements and correlated them with all the medical records from birth to diagnosis. As judicial experts in France are independent of all parties and lawsuits and work only with and for an independent judge, there was no conflict of interest.

Postmortem considerations are excluded from this review.

What do we learn from perpetrator statements?

In Starling's article [3], perpetrators admitted to abuse in 81 of 453 cases of inflicted traumatic brain injury (80 involved an acute and/or chronic subdural hematoma and one involved an isolated subarachnoid hemorrhage). In 69 cases, there was enough information provided to define the mechanism as impact alone in 29%, shaking alone in 46%, and a combination of impact and shaking in 25%. Retinal hemorrhage was seen in 83%. The mean age was fairly low (3.5 months, range: 0.5-52 months) and the sex ratio was 35% female (28/81). Death occurred in 19% of patients. The most common initial symptoms reported by the perpetrators were hypotonia (36%), seizures (31%), vomiting (30%), loss of consciousness (28%) and breathing problems (26%). Information about the time between injury and symptoms was available in 57 cases. Most of the perpetrators (91%, or 52/57) reported symptoms immediately after the injury was inflicted. Interestingly, none of the five infants (9%) in whom the symptoms were described as delayed was observed closely in the period immediately following the injury. In both Biron's [4] and Willman's [5] articles including 52 and 95 cases of inflicted trauma, respectively, the initial symptoms were described as occurring immediately after the injury if no epidural hematoma was present [5].

Our series also showed the classic demographic data [2]. The male-to-female ratio was 2:14 (45 boys, 21 girls). The median age was 4.4 months (3 weeks-41 months). All of the perpetrator statements described extremely violent shaking. Head impact was reported fairly infrequently (12%, or 8/66). Ophthalmological examination was performed on 65 children and found retinal hemorrhage in 86% of cases. At the time of the diagnosis, 44% of children (29/66) had bruising, including on the face (50%) and chest (11%). The skeletal surveys revealed fractures in 36% (24/66) of patients.

In 53 cases, the perpetrator was asked during questioning to describe the initial symptoms presented by the baby. In 100% of cases, changes in behavior were described immediately after the shaking, or even during the shaking. The perpetrator described the infant as having a period of "calm or silence" ("the baby stops crying") or a period of tiredness/sleeping (55%, or 29/53), hypotonia (41.5% or 22/53), loss of consciousness (38%, or 20/53), breathing problems (24%, or 13/53) or pallor (15%, or 8/53). Immediate vomiting was described in 11% (6/53) of cases. The more severe the symptoms, the faster medical help was sought.

In the subsequent time period, i.e. from approximately 30 min to 15 h after the shaking ended, the perpetrators reported abnormal movements that we have interpreted as seizures (32%, or 17/53), secondary vomiting without diarrhea or fever (9%, or 5/53), or focal neurological deficits (6%, or 3/53 cases) leading to a trip to the emergency department. In those cases, the earliest symptoms were often missed, probably because the child fell asleep.

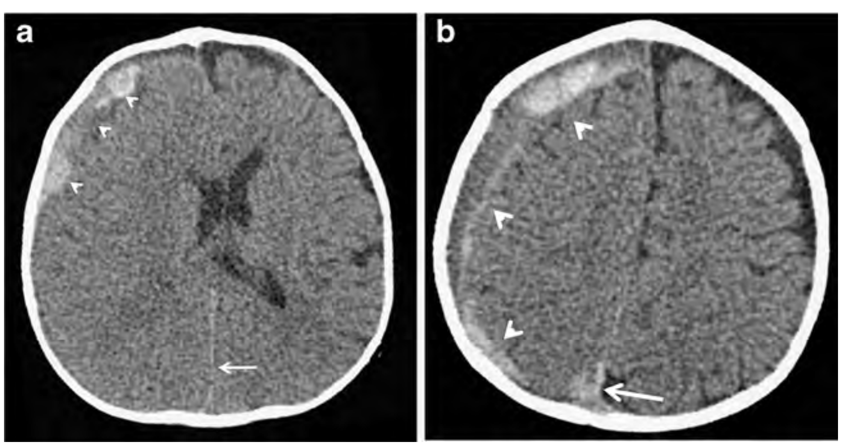

Fig. 1 Typical shaken baby syndrome/abusive head trauma. **a**, **b** CT of an 8-month-old boy presenting with loss of consciousness, left hemiparesis, seizures and bilateral retinal hemorrhages. Subdural hematoma of heterogeneous density is shown in the right frontotemporal area (*arrowheads*). Mass effect is visible with midline shift, compression of the right ventricle and blurring of the ipsilateral sulci. There is subtle hyperdensity of the posterior part of the inter hemispheric fissure (*arrows*)

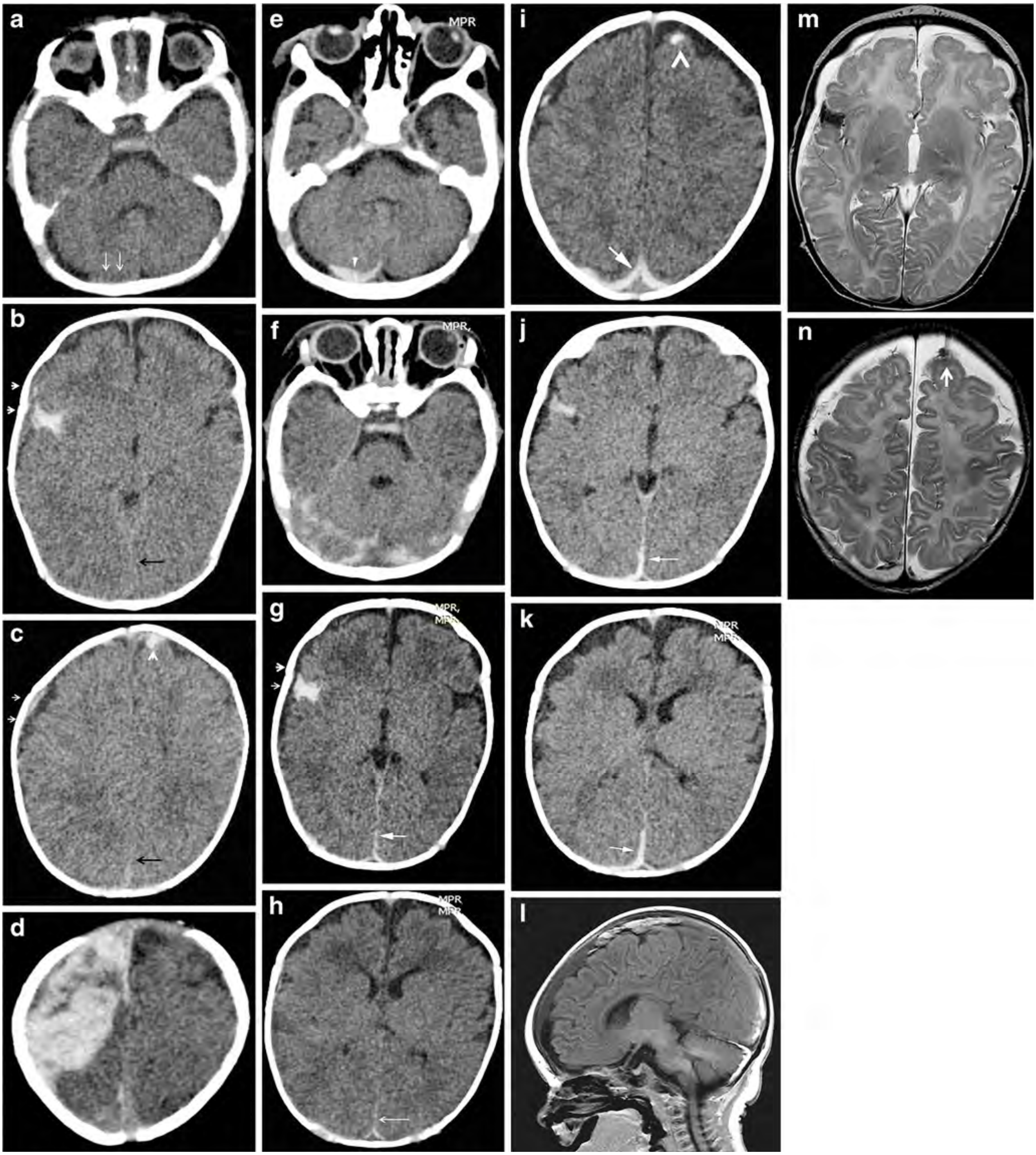

Fig. 2 Changes in subdural hematoma densities over time. The father of this 6-week-old term boy admitted one episode of violent shaking with immediate symptoms. **a**-**d** CT at Day 0 when the neonate presented with pallor, seizures, bruising and right retinal hemorrhages. An isodense subdural hematoma is seen in the posterior fossa (**a**, *arrows*), subarachnoid hemorrhage in the right lateral sulcus (**b**) associated with a thin right frontotemporal subdural hematoma (**b**, **c**, *white arrows*). The interhemispheric fissure appears almost normal (**b**, **c**, *black arrow*). Small hyperdense clot is seen in the subdural frontal space on the left side (**c**, *arrowhead*). A large hyper dense clot is located at the convexity on the right side (**d**) **e**-**i** CT at Day 1. A hyperdense subdural hematoma is now seen in the posterior fossa (e, *arrowhead*, and **f**) with a thinner right frontotemporal subdural hematoma (**g**, *short arrows*). The interhemispheric fissure becomes hyperdense (**g**-**i**, *long arrow*). Small hyperdense frontal clot is seen on the left side (**i**, *arrowhead*). **j**, **k** CT at Day 3. Increasing of the hyperdensity of the interhemispheric fissure (*arrow*). Note also the re-expansion of the sulci. (**l**-**n**): MRI at Day 4, T1-weighted spin-echo, right parasagittal slice (**l**) and T2-weighted fast spin-echo axial slices (**m**, **n**) confirmed the hemorrhages and a left frontal hemorrhagic spot that likely corresponds to a bridging vein thrombosis (**n**, *arrow*)

Dating based on imaging is inaccurate

Estimating the age of subdural hematoma with neuroimaging is imprecise and it would be more accurate to use the term "staging" rather than "dating." In theory, there are four stages: hyperacute, with an isodense appearance, less than 3 h old; acute, with a hyperdense appearance, less than about 10 days old; subacute, with an isodense appearance, 2–3 weeks old; and chronic (old), with a hypodense appearance, more than 3 weeks old [7]. On CT, acute bleeding shows high attenuation if the blood has clotted normally. In our experience of abusive head trauma, however, more than half of subdural hematomas in the frontotemporal region show a mixture of low, high and intermediate densities that is difficult to interpret (Fig. 1). Moreover, analysis of subdural hematoma density in abusive head trauma often reveals a combination of multiple subdural hematomas with different attenuation [4]. Interestingly, the terminology used to describe the attenuation of extra-axial hemorrhage on CT varies considerably between studies; "old" is used to qualify a hypodense subdural hematoma, and "acute" is often used without additional detail about the density, thereby perpetuating the confusion [8].

In fact, several factors can affect the appearance of subdural hematoma on imaging studies, and these can vary from day to day. Examples include the hemoglobin level, the concentration and hydration state of the red blood cells, the integrity of the cell membranes, the protein content of the blood clot, the sedimentation rate, clotting disorders, the amount of cerebrospinal fluid within the collection and the presence of an old hematoma (Fig. 2) [9]. Thus, an acute hyperdense subdural hematoma can be homogeneous or heterogeneous (mixed density pattern) for 8–10 days, as influenced by these factors. Some case studies have reported traumatic tears in the arachnoid membranes leading to a mixture of cerebrospinal fluid and blood in an acute subdural hematoma [10]. In particular, it is important to remember that a pattern of heterogeneous or multilayered densities within the subdural hematoma does not necessarily imply repeated injury, since there is ample documentation that subdural hematomas may rebleed spontaneously due to the presence of inflammatory membranes with newly formed capillaries (Fig. 3) [1, 2, 11]. In addition, subdural hematomas in the posterior fossa and interhemispheric fissure only become evident – i.e. marked by hyper density – a few hours or days after the first symptoms (Fig. 2) [7].

Patterns of time-related MRI signal changes within subdural collections can also be used to date the traumatic event, but they are more difficult to interpret than

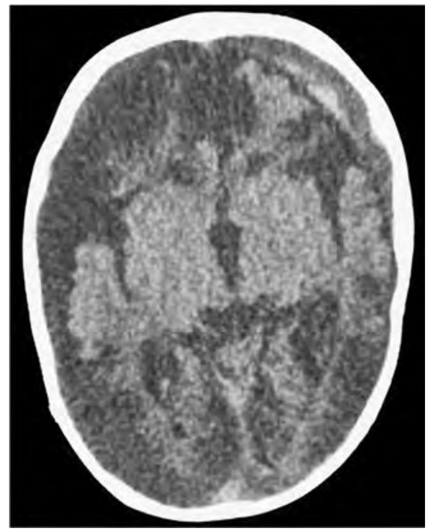

Fig. 3 CT 3 months after an acute shaking episode in a child (boy) who had been in protective custody since the diagnosis of shaken baby syndrome/abusive head trauma at age 4 months. Major brain atrophy and spontaneous hyperdense rebleeding in the left frontal subdural space is seen

CT dating. For example, a hyperacute subdural hematoma (less than 24 h old) is hypo- or isointense on T1-weighted sequences and hyperintense on T2-weighted sequences. The signal intensity will decrease on T2-W sequences in the acute stage (less than 3 days) and then increase on T1-weighted sequences; the subacute stage is considered to last for up to 2 months. The hemosiderin deposits (low signal at T2-weighted gradient echo) can last months or even years. Several papers have, however, pointed out the lack of evidence in dating subdural collections [1, 2, 7–9, 11]. Of interest is that membranes within subdural hematoma begin to form after 2 weeks and may be exquisitely demonstrated with MRI [12].

Parenchymal brain or cervical cord abnormalities are interesting to consider when estimating the age of the causal injury. In particular, diffusion-weighted imaging (DWI) is invaluable in demonstrating acute cytotoxic cell edema, which lasts for a few days – usually less than a week (Fig. 4). However, while a strong association between hypoxic-ischemic injury and abusive head trauma has been well-established, the mechanism of hypoxic-ischemic injury is not yet fully understood [13, 14]. It may be related to initial cardiorespiratory arrest and/or to seizures through excitotoxic processes. While the presence of cytotoxic edema indicates early hypoxic-ischemic injury, it does not preclude a traumatic injury from a few days earlier, since the cytotoxic brain edema may be secondary to seizures, which may themselves be delayed after the shaking.

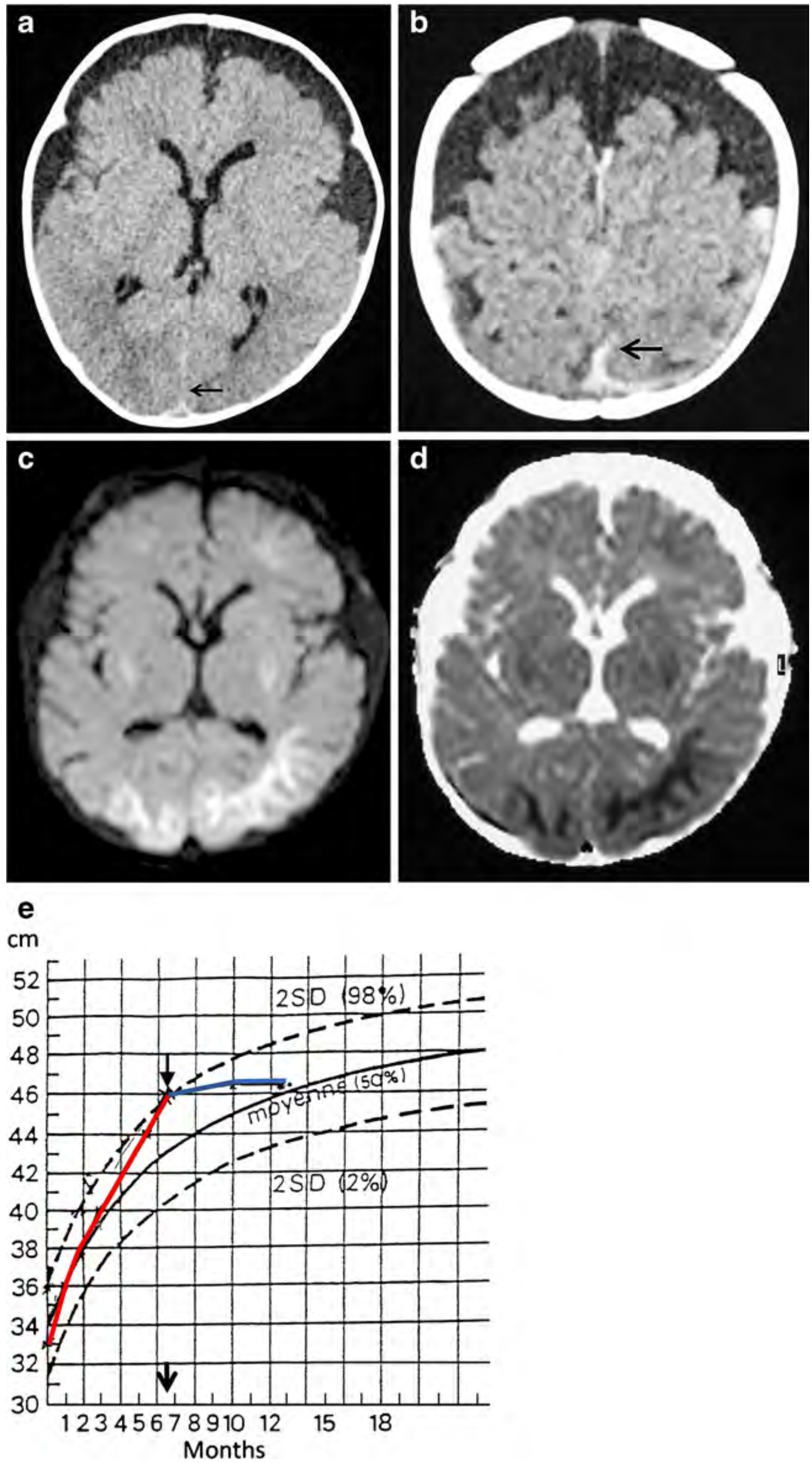

Fig. 4 A 6-month-old girl in a coma due to acute abusive head trauma. **a**, **b** CT at Day 0. Hypodense bilateral anterior subdural hematoma (absence of sulcal enlargement) is combined with hyperdense subdural hematomas in the interhemispheric fissure and at the convexity (*arrows*). Subtle parenchymal hypodensities are seen in the temporooccipital areas (**a**). **c**, **d** Three days later, diffusion-weighted MRI (**c**) and apparent diffusion coefficient (ADC) map (**d**) show multiple areas of cytotoxic edema (decreased ADC) in the occipital white matter and the gray-white matter junctions in the frontal lobes and basal ganglia. This age-different pattern is well correlated with a rapid increase in head circumference since age 2 months **e** Head circumference chart shows a rapid increase since age 2 months followed with a stagnation (arrow) since the acute event

Some recent papers have highlighted the possibility of identifying bridging vein thrombosis secondary to rupture based on patterns of tubular or round-shaped clots at the vertex [14, 15] (Fig. 5). These clots are

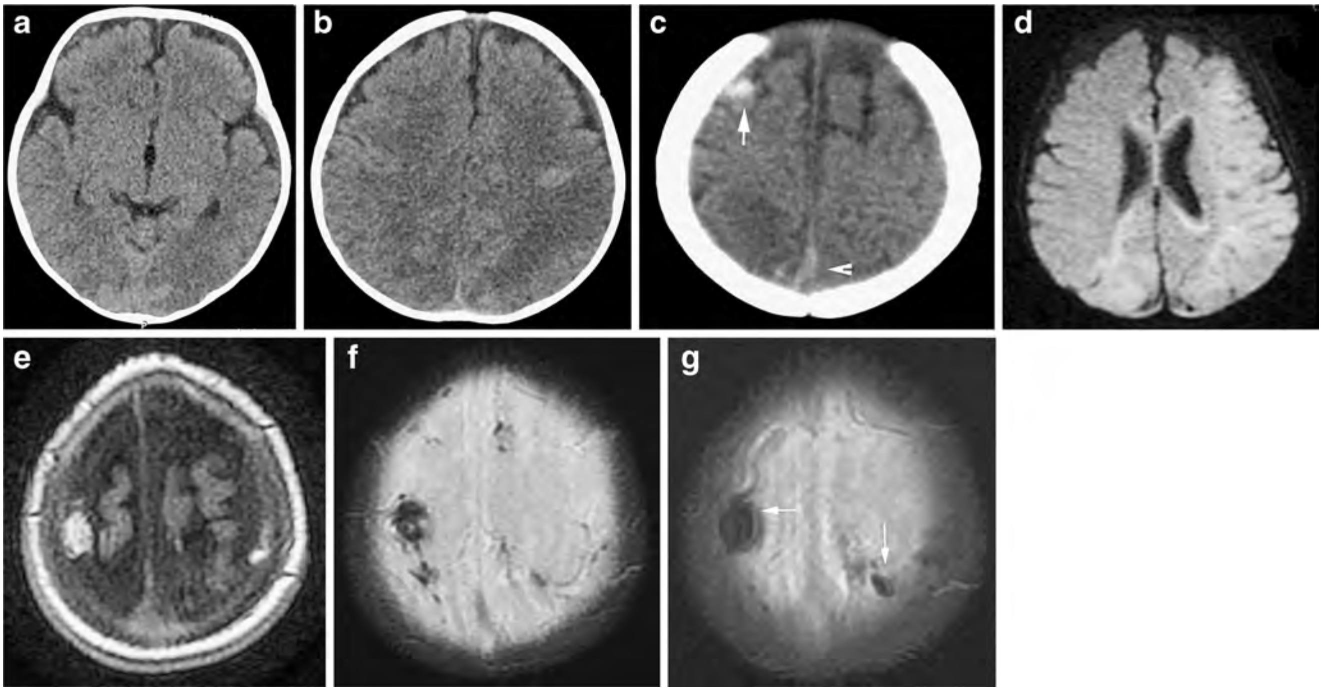

Fig. 5 A 3-month-old boy who suffered abusive head trauma. **a-c** CT at admission shows thin frontotemporal subdural hematomas of heterogeneous low density and large parenchymal hypodensities with loss of *gray/white* matter contrast due to hypoxic-ischemic injuries (**a**, **b**). There is a hyperdense spot at the vertex on the right side (**c**, *arrow*) and mild hyperdensity in the interhemispheric fissure (**c**, *arrowhead*). **d-g** MRI 2 days later with diffusion-weighted imaging (**d**), T1-weighted inversion recovery (**e**) and T2*-weighted imaging (**f**, **g**) confirm hypoxic-ischemic injury predominantly on the left side (**d**) and rounded/tubular spots of hemosiderin at the convexity corresponding to bridging vein thrombosis (**e-g**)

better demonstrated by MRI (gradient echo or susceptibility imaging sequences) than by CT. Not only are they invaluable in diagnosing abusive head trauma by providing direct proof of acceleration/deceleration trauma, they also indicate recent injury if they present with an acute pattern (hyperdense appearance on CT less than about 10 days old) according to the usual changes of a hematoma overtime [7, 9]. However, due to the time interval between in vivo imaging and autopsy, there is no study that specifically correlates the histological features of bridging vein thrombosis with the imaging patterns.

It is impossible to estimate the age of a skull fracture because healing takes a few months and there is no periosteal thickening [16]. And while the presence of a scalp hematoma indicates an acute impact, the volume of the swelling will depend on the conditions of the impact and the status of the child at the time of the impact, i.e. hypovolemic shock, anemia, etc. Nor are non-skull skeletal fractures, which are found in approximately one-third of the cases in our series [6], of any help in dating the causal event because healing appears within 8–10 days [17]. Thus, imaging cannot currently be used to accurately date the causal event.

Is it possible to identify repeated episodes of violence?

In 55% of the cases, the offenders admitted that shakings took place over a period of weeks or months, and were repeated from 2 to 30 times (mean: 10) because it stopped the infant's crying (62.5%) [6]. Extending our investigation from 29 to 66 cases confirms these data.

Knowing the high prevalence of habitual shaking brings up two issues. First, neuroimaging-based dating is even more uncertain in non-accidental than in accidental trauma because the latter are a onetime occurrence. Second, how can we recognize, on the basis of neuroimaging, the age-different patterns that strongly indicate at least two distinct episodes of violence with any confidence?

We have seen that because it is influenced by a number of factors, the attenuation within one area of subdural hematoma cannot be used as an indicator of age-different injuries. In particular, the frequently observed mixed density/intensity pattern is not necessarily associated with repeated episodes of violence. We therefore hypothesize that only subdural hematomas with two different densities in two distant locations on CT can be considered an indicator of age-different injuries. Practically, the sites of

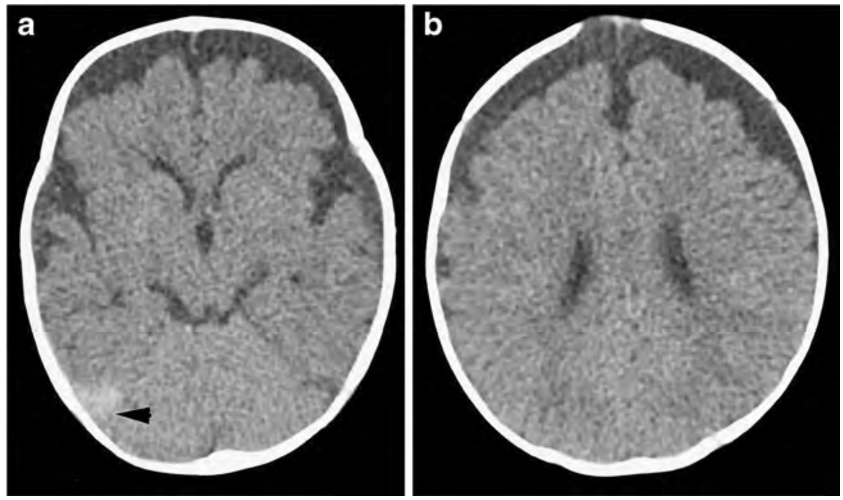

Fig. 6 Age-different pattern in abusive head trauma. **a**, **b** CT in a 6-month-old boy. Hypodense bilateral frontal subdural hematomas are combined with mild hyperdense subdural hematoma of the tentorium (*arrowhead*). In a statement, the caretaker admitted repeated daily shakings over a period of weeks. Episodes of vomiting, feeding troubles and pallor were reported by the parents 8 days prior to admission for loss of consciousness

subdural hematomas can be simply divided in five locations, which are (1) right and (2) left frontoparietotemporal subdural spaces, (3) interhemispheric fissure and (4) the tentorium. The fifth location specifically considers the vertex (five last reformatted upper slices of 3 mm in thickness) in which round or tubular hyperdense clots are frequently observed in abusive head trauma. Thereby, for example, an age-different pattern might be a hypodense frontoparietal or frontoparietotemporal (older than 10–15 days) in combination with a frankly hyperdense (younger than approximately 10 days) hematoma in the posterior fossa. Also, an age-different pattern can be marked

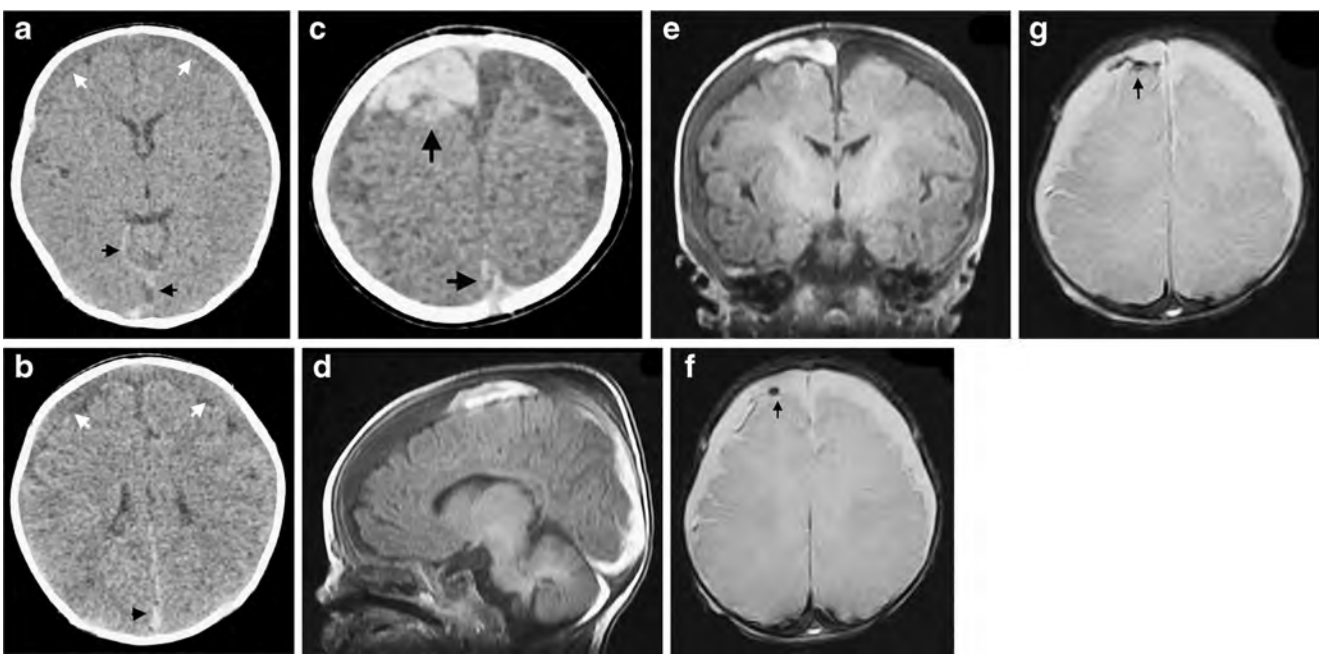

Fig. 7 Age-different pattern in abusive head trauma. The father admitted at least eight or nine episodes of violent shaking to “calm” his 2-month-old daughter, who then fell asleep. No retinal hemorrhages were seen. **a**-**c** CT at admission for loss of consciousness after 5 days of abnormal vomiting. The combination of intermediate-density frontal subdural hematomas (*white arrows*) with frankly hyperdense subdural hematomas in other locations, e.g., tentorium and interhemispheric fissure (*black arrows* and *arrowheads*), and hyperdense clots at the right convexity is suggestive of an age-different pattern. d-g MRI 4 days after admission with T1-weighted inversion recovery (**d**, **e**) and T2*-weighted imaging (**f**, **g**) confirms the CT features and helps demonstrate bridging vein thrombosis (**f**, **g**, *arrows*)

with a hypodense frontoparietal subdural hematoma associated to hyperdense clots at the vertex (Figs. 6 and 7). While migration of subdural hematomas due to gravity may be seen, the detection of new hyperdensities far from the lateral hypodense (old) subdural hematoma is very likely evidence of true new bleeding [6, 8, 18]. Conversely, in cases in which all the sites of bleeding are mostly consisting of hyperdensities, whether homogeneous or heterogeneous, it's not possible to conclude to an age-different pattern. Indeed, in our personal series including 66 cases for which detailed confessions from police inquiries or judicial investigations were available, we have evaluated this age-different pattern of two frankly different densities in two distant locations (at least one hypodense subdural hematoma and one hyperdense subdural hematoma/clot among the five defined locations) and we have found that it was strongly associated with confessions of repeated episodes of violence (81%, or 26/32), yet present in only 44% (15/34) cases of a single episode of violence (P=0.006) (results presented at the international conference on shaken baby syndrome/abusive head trauma, Paris, May 4–6, 2014). Of course, it is not possible to determine how many episodes of violence have occurred.

However, we have also observed a lack of age-different patterns despite admissions of repeated shaking. We have interpreted this as the consequence of brain edema, where the swelling masks a previous old subdural hematoma (Figs. 8 and 9) [6]. Also, all hypodense subdural hematomas without age-different pattern may also be the result of abusive head trauma with habitual repetitive shaking [6]. On the other hand, we assume that the false-positive age-different pattern may, however, be due to "minimized" confessions in some cases [6].

Interestingly, it was much easier in our experience to assess the age-different pattern of subdural hematomas with CT than with MRI, due to the highest sensitivity of MRI to hemoglobin degradation products and thus the complexity for reasoning in dating the hemorrhages with MRI. Nevertheless, MRI can help to demonstrate repeated violence as the analysis of parenchymal injuries can also provide strong indicators for assessing the pattern of "age-different injuries," e.g., the association of acute hypoxic-ischemic injuries or venous infarcts, exquisitely depicted on DWI sequences, with a fluid-like appearance of the subdural hematoma, close to the cerebrospinal fluid signal intensity (Figs. 4 and 6).

A fluid-like appearance of subdural hematoma may be associated with benign enlargement of subarachnoid spaces, if the sulci are also enlarged. An analysis of the head circumference chart can be very helpful: a rapid, unexplained increase in head circumference in the few weeks or months prior to admission may be an indicator of previous subdural hematomas, in combination with mild symptoms (Fig. 4). We should also emphasize that there are no consistent data in the literature to support the hypothesis that benign enlargement of subarachnoid spaces predisposes infants to subdural hematomas [1, 2, 19]. Conversely and importantly, sulcal expansion may be a consequence of abusive head trauma, in the context of brain atrophy and/or impaired cerebrospinal fluid resorption (Fig. 10).

In addition to neuroimaging, other features must be carefully analyzed when assessing repetitive violence. Close attention should be paid to the child's medical history and previous events reported by the parents and caregivers, to look for earlier, mild signs that may prove invaluable in identifying previous violence. Clinical indicators of previous shaking may include unexplained

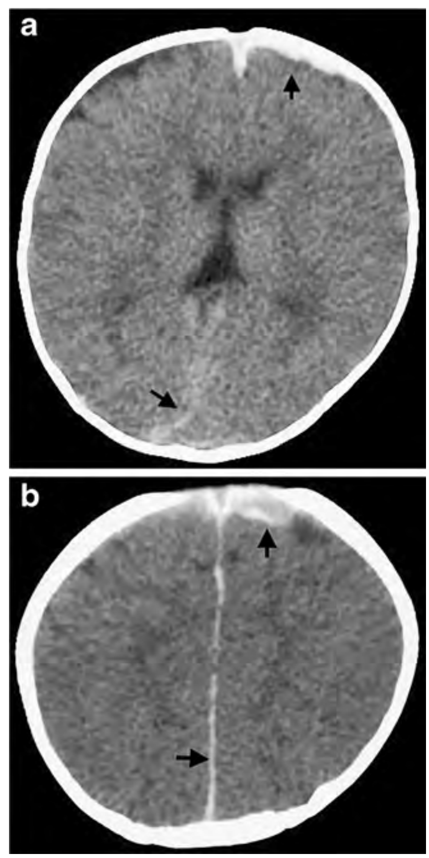

Fig. 8 Lack of an age-different pattern despite a number of violent shakings admitted by the mother of this 5-month-old girl. **a**, **b** CT shows only a thin hyperdense subdural hematoma over the left frontal lobe and in the interhemispheric fissure (*arrows*). The brain edema may mask a previous hematoma

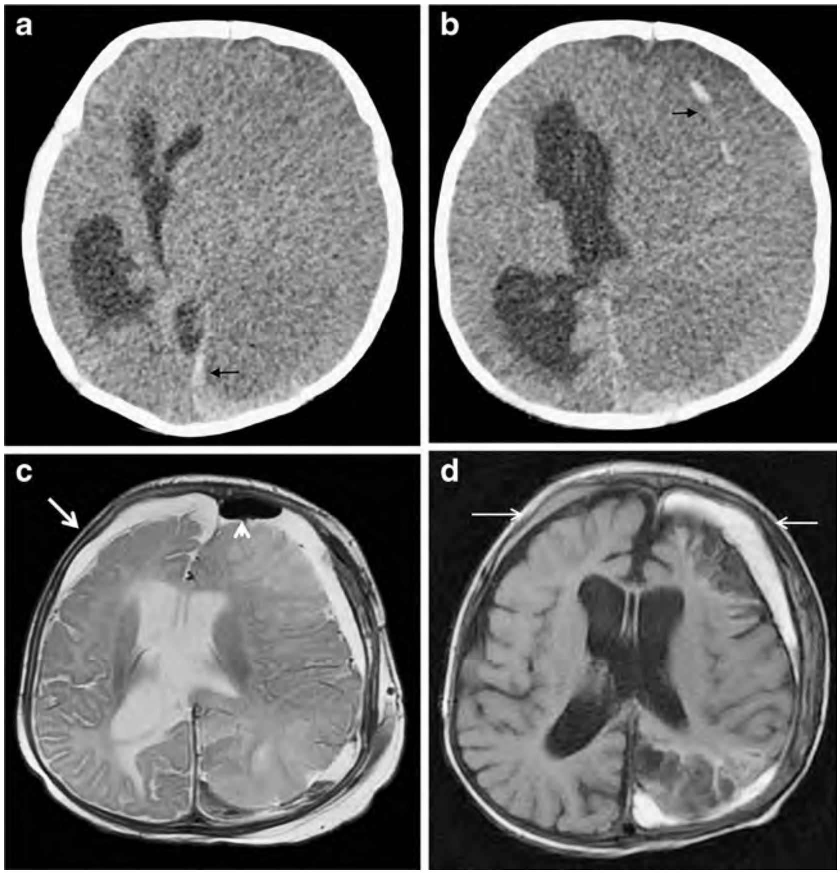

Fig. 9 No age-different pattern despite the father admitting to several previous episodes of violent shaking, slaps and impacts to this 3-month old boy presenting with seizures and hemiplegia. A rapid increase in head circumference was noticed over the previous 2 weeks. **a**, **b** Initial CT shows a large, low-density subdural hematoma with areas of mild hyperdensity (*arrows*) located over the left hemisphere and in the inter-hemispheric fissure. Major compression and displacement of normal structures are visible. **c** T2-weighted MRI a few hours after evacuation reveals a right subdural enlargement (*arrow*) and parenchymal injuries of the left hemisphere marked with a loss of contrast between gray and white matter. Post-surgical air is seen in the left frontal subdural space (*arrowhead*). **d** Fluid-attenuated inversion recovery MRI 3 weeks later show enlarged sulci and ventricles due to atrophy. There are areas of necrosis in the frontal and occipital lobes on the left side and persistence of bilateral subdural hematomas (*arrows*), predominantly on the left side

vomiting without diarrhea or fever and/or unexplained bruises or oral injury in nonambulatory children, in the medical records from birth to the time of diagnosis [20].

Painstaking examination of a high-detail skeletal survey to look for healed fractures is crucial, as these are a strong indicator of previous violence [21–23]. In doubtful cases, particularly for rib fractures, it may be helpful to do a skeletal survey after 10 days, as this can provide evidence of a healing injury not apparent on initial radiographs [21–23].

In clinical practice, there is no scientific data to aid in estimating the age of a bruise from its color, since bruise characteristics are influenced by the location, the skin color, the force of the injury, and the depth and extent of subcutaneous extravasation [24].

Retinal hemorrhage is a major indicator of possible abusive head trauma, though it is absent in approximately 15% of cases. Ophthalmological examination should include full indirect examination through a dilated pupil by an ophthalmologist within 72 h of the acute presentation, and ideally within the first 24 h. However, ophthalmological examination is usually not reliable enough to determine whether the injuries are age-different, or to date them [1, 2, 25].

Conclusion

Although perpetrator admissions are not scientific evidence, they provide information crucial to our understanding. The high prevalence of repeated shaking (50%) is probably still an

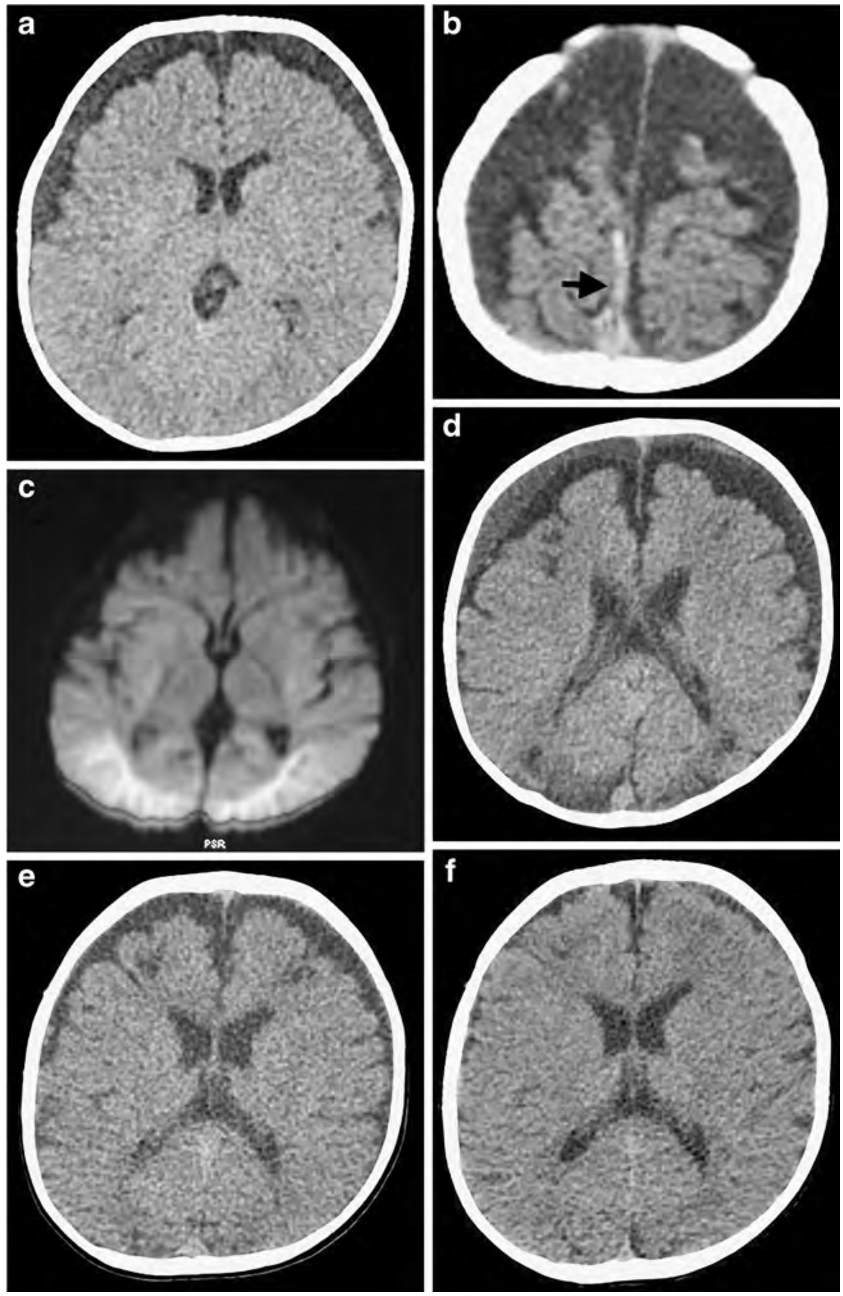

Fig. 10 Evolution of subdural hematomas. The caregiver admitted to three episodes of shaking a 6-month-old boy over a period of a few weeks. **a**, **b** First CT at admission for seizures and hypotonia shows bilateral frontotemporal subdural hematomas of low intermediate density with mild interhemispheric hyperdensity at the vertex (*arrow*). **c** Diffusion-weighted MRI 24 h later shows bilateral hyperintensities in the temporo-occipital areas related to recent hypoxic-anoxic injuries. **d** CT 3 months later demonstrates changes in the densities of the subdural hematomas. **e** CT 6 months later shows enlargement of both ventricles and sulci due to atrophy. **f** CT 14 months later shows mild enlargement of ventricles and sulci related to atrophy

underestimate. Children do not behave normally immediately after shakings, and the time of onset of even mild symptoms appears to be the best clue for dating the incident. Brain imaging offers wide ranges for dating the causal event. The density/intensity pattern in a single subdural hematoma location provides no reliable clues for assessing repeated violence. However, brain imaging is a strong marker to argue in favor of age-different injuries, i.e. repeated violence, using strict criteria. MRI must be analyzed in conjunction with CT to evaluate the age of a subdural hemorrhage. Most importantly, all of the child's previous clinical and radiologic data must be carefully studied and correlated to provide accurate information on the date and repetition of the trauma.

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Conflicts of interest None

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