

What neuroimaging should be performed in children in whom inflicted brain injury (iBI) is suspected? A systematic review

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AIMS: To investigate the optimal neuroradiological investigation strategy to identify inflicted brain injury (iBI).

MATERIALS AND METHODS: A systematic review of studies published between 1970–2008 in any language was conducted, searching 20 databases and four websites, using over 100 keywords/phrases, supplemented by hand-searching of references. All studies underwent two independent reviews (with disagreements adjudicated by a third reviewer) by trained reviewers from paediatrics, paediatric neuroradiology and related disciplines, using standardized critical appraisal tools, and strict inclusion/exclusion criteria. We included primary studies that evaluated the diagnostic yield of magnetic resonance imaging (MRI), in addition to initial computed tomography (CT), or follow-up CT or ultrasound in children with suspected iBI.

RESULTS: Of the 320 studies reviewed, 18 met the inclusion criteria, reflecting data on 367 children with iBI and 12 were published since 1998. When an MRI was conducted in addition to an abnormal early CT examination, additional information was found in 25% (95% CI: 18.3–33.16%) of children. The additional findings included further subdural haematoma, subarachnoid haemorrhage, shearing injury, ischaemia, and infarction; it also contributed to dating of injuries. Diffusion-weighted imaging (DWI) further enhanced the delineation of ischaemic changes, and assisted in prognosis. Repeat CT studies varied in timing and quality, and none were compared to the addition of an early MRI/DWI.

CONCLUSIONS: In an acutely ill child, the optimal imaging strategy involves initial CT, followed by early MRI and DWI if early CT examination is abnormal, or there are ongoing clinical concerns. The role of repeat CT imaging, if early MRI is performed, is unclear, as is the place for MRI/DWI if initial CT examination is normal in an otherwise well child.

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Introduction

Physical abuse is a leading cause of brain injury in infants, which is associated with a 31–45%

morbidity^{1–4} and 6–26% mortality.^{1–5} These children, predominantly aged less than 2 years, present with varying symptoms from marked neurological compromise and impaired levels of consciousness to a child with relatively mild symptoms.^{1,3,5,6} They manifest a variety of intracranial neuropathological conditions, which includes extra-axial haemorrhages with or without brain injury. Diagnosis relies upon sensitive neuroimaging. Current techniques available include computed tomography

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(CT) where the child is exposed to the equivalent of 10 months background irradiation⁷ and/or magnetic resonance imaging (MRI) under sedation or general anaesthetic. Current published clinical guidelines recommend that CT should be the initial investigation in the acute situation when inflicted brain injury (iBI) is suspected.⁷ The American Academy of Pediatrics (AAP) and American College of Radiology (ACR) have both issued guidelines, which vary in their emphasis on the clinical indications and the need for, or timing of, second-line imaging. Parents, and some clinicians, have raised concerns regarding the risk to the child of radiation, or the need for general anaesthetic, and these must be balanced against the risk of missing these injuries, and potentially returning a child to the abusive environment. However, to ensure that the clinical management is timely and appropriate and that all intracranial injuries are fully delineated, it is essential that the optimal imaging strategy is chosen. There is increasing recognition that certain patterns of neuroimaging abnormalities are strongly associated with iBI,^{8,9} and identifying these will inform the Child Protection Agency and court proceedings. To define an evidence-based approach to this, a systematic review was undertaken to define the optimal neuroimaging that should be performed to identify iBI in children.

Materials and methods

Literature search

An all-language literature search of original articles published from 1970 through January 2008 was

undertaken (Fig. 1). These dates were selected because they covered the time period when CT and later MRI became available. The following databases were searched: ASSIA (Applied Social Science Index and Abstracts), ChildData, CINAHL (Cumulative Index to Nursing and Allied Health), EMBASE (Excerpta Medica Database), MEDLINE (Medical Literature Analysis and Retrieval System Online), MEDLINE In-Process, Scopus, SIGLE (System for Information on Grey Literature in Europe), Trip Plus, Social Care Online, ISI Proceedings, ISI Science Citation Index, ISI Social Sciences Citation Index, and all EBM reviews (ACP Journal Club, Database of Abstracts of Reviews of Effects, Cochrane Central Register of Controlled Trials, Health Technology Assessment, Cochrane Database of Systematic Reviews, National Health Service Economic Evaluation, Cochrane Methodology Register).

In addition to the bibliographic databases, the following websites were searched: the Child Brain Injury Trust (CBIT) www.cbituk.org, Child Welfare Information Gateway (Formerly National Clearing House on Child abuse and neglect) <http://www.child-welfare.gov/>, International Society for Prevention of Child Abuse and Neglect (ISPCAN) <http://www.ispcan.org/>, and the National Center on Shaken Baby Syndrome <http://www.dontshake.com/>.

To increase the sensitivity of the search, the reference lists and bibliographies of all the literature obtained were hand-searched. Citations from the main and supplementary searches were transferred to a database, used to coordinate the review. Keywords used in the search are listed in Appendix A.

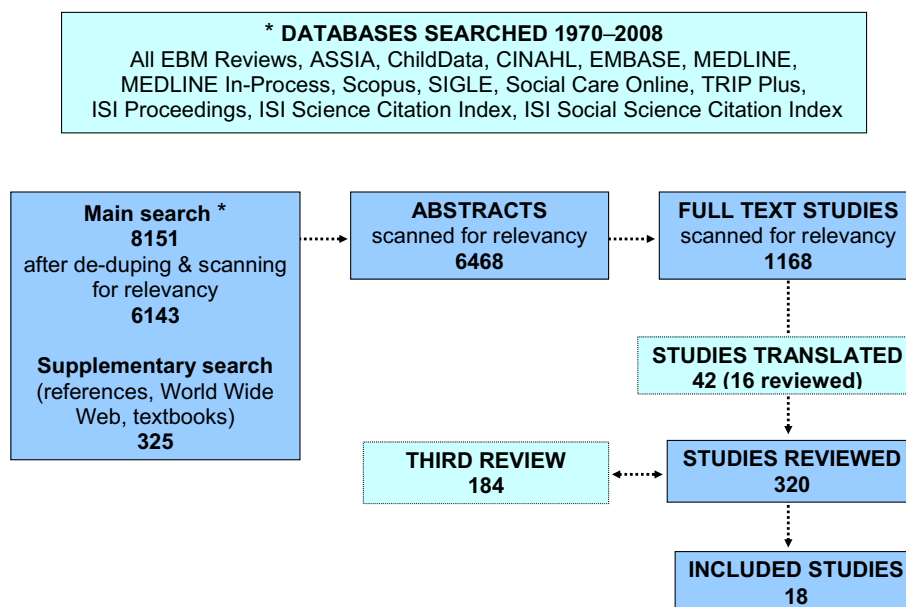


Figure 1 Main phases and number of studies identified at each stage.

Quality assessment

The inclusion and exclusion criteria for the selection of studies are listed in Table 1. Each study underwent two independent reviews by members of a group of some 30 reviewers, comprising paediatricians, radiologists, neuroradiologists, forensic pathologists, and ophthalmologists involved in child protection work. Where necessary, disagreements were adjudicated by a third reviewer. All the reviewers had received training in critical appraisal and had access to a standardised specifically designed computer-based critical appraisal resource. Each study was critically appraised using data-extraction sheets, critical appraisal forms and evidence sheets based on NHS Centre for Reviews and Dissemination.^{10–12}

Studies were graded for quality of study design and confirmation of diagnosis of abuse (ranking of abuse as shown in Table 2). This ranking is a previously reported method¹³ of defining the likelihood that those children described as “abused” in

Table 2 Ranking of criteria used to define abuse

Ranking	Criteria used to define abuse
1	Abuse confirmed at case conference or civil or criminal court proceedings or admitted by perpetrator or independently witnessed
2	Abuse confirmed by stated criteria including multidisciplinary assessment
3	Abuse defined by stated criteria
4	Abuse stated but no supporting detail given
5	Suspected abuse

a given study had undergone a comprehensive clinical and social assessment, where a rank of 1–3 gives the greatest confidence that the diagnosis of abuse did not rest solely on the physical injury found.¹³ This is a crucial quality standard, as it is vital to rely on evidence other than medical findings in determining an abusive cause. The non-iBI cases included accidental trauma and medical causes of brain injury. Where necessary, authors were contacted for primary data or further information regarding confirmation of abuse.

Definition of iBI

Children who had suffered intracranial injuries (extra-axial bleeding, intraparenchymal haemorrhage, diffuse axonal injury, hypoxic ischaemic injury, or any combination of the above) as a result of physical abuse.

Statistics

The aim of the study was to analyse the relative value of an additional MRI examination to the initial CT examination and to estimate the proportion of cases in which an additional MRI would provide supplementary information to an initial CT examination. Three included papers^{1,6,14} were suitable for a comparison of CT and MRI. These papers had in common the retrospective selection of cases based on a diagnosis of iBI, and sufficiently detailed reporting of the additional findings and numbers of children undergoing CT and MRI.

Unfortunately, not all children underwent both investigations, so there remains the possibility that, had MRI examinations been performed (when in fact they were not), additional information would have been picked up. In these cases, it was assumed that such MRI examinations would have revealed the same information as the CT examination. Using this conservative assumption, the proportion of cases in which an MRI examination provided additional information was computed.¹⁵

Table 1 Inclusion and exclusion criteria

Inclusion criteria:

- Primary studies of children aged 0<18 years
- Undergoing brain CT and additional investigations (repeat CT or brain MRI or ultrasound) to identify intracranial abnormalities as a consequence of iBI
- Ranking of abuse within study of 1–3
- Fatally and non-fatally abused children with ante-mortem radiology
- All language studies
- Time period 1970–January 2008

Exclusion criteria:

- Studies of complications, management or prognosis of iBI
- Consensus statements or personal practice studies
- Single case studies
- Studies addressing exclusively post-mortem neuropathological findings
- Studies with mixed adult and child data, where the children’s data cannot be extracted
- Studies that lacked detail on individual imaging data or adequate comparison between CT and MRI
- Studies evaluating neuroimaging techniques that are not relevant to current practice
- Methodologically flawed studies
- Studies of head injuries restricted to isolated skull fractures, scalp injuries
- Spinal injuries
- Studies addressing the findings on an initial CT scan or MRI alone

CT, computed tomography; MRI, magnetic resonance imaging; iBI, inflicted brain injury.

Results

Fig. 1 summarizes the total number of studies identified and reviewed. Eighteen studies met the inclusion criteria reflecting data on 367 children with iBI.^{1,6,14,16–30} There were two cross-sectional studies,^{1,25} and the rest were case series or case studies. The age range of the children was up to 4 years in 16 of the 18 studies. The two exceptions^{25,30} included children up to 15 years of age. The mean age of all cases was available in 15 of the 18 studies^{1,14,16–24,26,27,29,30} and varied between 3 and 14 months, and the combined mean was 7.84 months. Only one³⁰ of the included studies was published prior to 1987.

Comparison of brain CT versus MRI

What is the value of MRI in children with abnormal CT examination results?

Seven studies^{1,6,14,16,23,24,26} compared the diagnostic yield of the initial abnormal CT with an early MRI in cases of iBI (Table 3). MRI was performed at varying time intervals after the initial CT examination (day 1 to 6 months). In all cases the initial CT examination was abnormal, not all children in the studies underwent MRI, and it was not always clear why certain children were selected for MRI.

Three studies^{1,6,14} were suitable for statistical analysis. Here, 73 of the 128 children underwent an additional MRI examination, and this provided new information in 32 children. A conservative estimate, using the statistical method detailed

above, is that in the population of children with subdural haematoma (SDH) or other intracranial abnormalities due to iBI detected via CT, an MRI would reveal new information in at least 25% (95% CI: 18.3–33.16%) of children.

A descriptive analysis of the nature of the additional findings was possible from seven studies.^{1,6,14,16,23,24,26} In 66/115 children who had undergone an MRI examination, the most common additional findings identified were further SDHs^{1,6,14,16,23,24,26} and additional subarachnoid haemorrhages (SAHs) that were not identified on the initial CT examination.^{1,16,24} The missed SDHs were in varying locations: occipital lobe, posterior fossa, subtemporal lobe, subfrontal lobe, convexity, and interhemispheric locations. Three studies reported that MRI gave additional information about the signal intensity of the SDHs.^{6,14,16} In addition, in three studies MRI demonstrated cranial shearing injury that was not apparent on CT.^{1,14,26} Ischaemia and infarction not seen on CT images were identified using MRI,¹ and it was confirmed that MRI was superior to CT at detecting parenchymal haemorrhages.^{1,14,16} Cerebral contusions were identified equally well or better on MRI than on CT, as demonstrated in five of 16 children, where details given,²⁶ Sato et al.²⁶ noted, however, that SAHs were missed using MRI in four out of the 16 patients.

Is there any value in performing MRI in children with normal initial CT examinations?

Three studies reported cases where the initial CT was interpreted as normal.^{16,23,26} Morad et al.²³

Table 3 Additional findings in magnetic resonance imaging (MRI)

Authors (year)	Study type	Age	No. of MRI /no. iBI ^a	Timing of CT examinations	Timing of MRI examination	Additional findings on MRI				
						SDH/SAH	HSI	PL	PH	SI
Datta et al. (2005)	Case series	<2 years	25/49	Unavailable	1–12 days	>7	6	5	0	0
Ghahreman et al. (2005)	Cross-sectional	<46 months	37/65	Unavailable	1–10 days (median 5 days)	8	0	4	3	3
Morad et al. (Dec 2004)	Case series	<27 months	3/8	On admission	4–5 days	2	0	0	0	0
Morad et al. (Oct 2004)	Case series	<17 months	8/9	On admission	Four < 24 h, six at 3–7 days, two at 1–6 months	4	0	0	0	0
Hoskote et al. (2002)	Case series	<7 months	11/14	N/A	N/A	3	7	1	1	1
Chabrol et al. (1998)	Case series	<8 months	12/12	N/A	2–20 days	9	3	2	2	0
Sato et al. (1989)	Case series	<4 years	19/19	N/A	N/A	15	0	5	0	5

CT, computed tomography; SDH, subdural haematoma; SAH, subarachnoid haemorrhage; HSI, haematoma signal information; PL, non-haemorrhagic parenchymal lesion (includes ischaemia, infarct, bland contusion); PH, parenchymal haemorrhage; SI, shearing injury; N/A, data not available.

^a No. of patients undergoing MRI examinations/no. of cases of inflicted brain injury.

reported on nine patients recruited by a worldwide listserv (i.e. an internet forum of specialists in child abuse) to identify cases of iBI whose CT was reported as normal. Eight of these underwent an MRI examination, and four were reported as normal. Those who had an abnormal MRI (four of the eight patients) presented with symptoms of vomiting/irritability ($n=1$), limp and crying with an unusual voice ($n=1$), seizures ($n=1$), and difficulty breathing ($n=1$). Three of the four with abnormal MRI examinations had rib and/or long bone fractures and all had severe retinal haemorrhages (RHs) and an abnormal neurological outcome. Of the four children with normal MRI examinations, all had RHs, two had rib and/or long bone fractures, one had seizures, irregular breathing, and lethargy, three had irritability, and three had a normal outcome. The abnormal findings in four children included subdural collections on MRI images performed 3–7 days after the CT examination (two had had a normal initial MRI examination). The authors did not state who provided the original CT reports, whether they were re-evaluated, or whether the children were in a place of safety between investigations. Only one image was reproduced in this study and there is some doubt as to whether the “normal” CT images collected for this report were truly normal; a “normal” CT illustrated (case 1) shows expanded extra-axial fluid spaces that are at least suspicious, if not diagnostic, of subdural collection.

Sato et al.²⁶ reported three patients with normal CT examinations where the corresponding MRI examinations demonstrated small SDHs, shearing injury, and a non-haemorrhagic cortical contusion, respectively. Information on the clinical

features in these cases was not available. Chabrol et al.¹⁶ reported a 2-month-old girl with apnoeic episodes and multiple fractures on skeletal survey, including rib fractures. The CT examination was reported as normal, but an MRI examination at 6 days showed a subdural collection interpreted as an old SDH (although this could have been an acute traumatic subdural hygroma) with a haemorrhagic right frontal contusion.

What is the value of performing diffusion-weighted imaging (DWI)?

In four studies (Table 4) DWI demonstrated additional findings that were not apparent on conventional MRI.^{18,21,22,28} This represents data on 30 children, all aged less than 2 years. Suh et al.²⁸ published a case series where children less than 2 years underwent MRI and DWI within 8 days of admission. The DWI abnormalities present indicated more extensive brain injury than could be identified on conventional MRI sequences. Suh et al.²⁸ also showed that the severity of injury on DWI correlated with poor outcome. The remaining studies, all published since 2006, conducted the MRI/DWI examinations within 5 days, where details were given. Küker et al.²¹ and McKinney et al.²² found abnormal diffusion patterns, in addition to the SDH seen on standard MRI. In both of these studies these early changes were found to correlate with ischaemic damage, and later poor prognosis. Dan et al.¹⁸ detailed four children all of whom had diffusion abnormalities detected on DWI, these were both cortical and subcortical, which were not evident on the early MRI images. All parenchymal haemorrhages were excluded

Table 4 Additional information from magnetic resonance imaging (MRI) with diffusion-weighted imaging (DWI)

Authors	Study type	Age	No. DWI/ No. iBI ^a	Timing of DWI ^b	Additional findings
McKinney et al. (USA) 2008	Case series	<14 months	2/11	Both at < 5 days	Diffuse cortical infarction, early subacute phase HIE
Dan et al. (Belgium) 2008	Case series	<9 months	4/4	All at < 5 days	Cortical and subcortical restricted diffusion, consistent with HIE and confirmed by later ischaemic changes on MRI.
Küker et al. (Germany) 2006	Case series	<6 months	4/4	Two at < 2 days Two after 2 weeks	Identified restricted diffusion of cortical and subcortical areas, which later developed necrosis
Suh et al. (USA) 2001	Case series	<22 months	20/20	Fifteen at < 48 h Five at < 5 days	In 81% of positive cases DWI revealed more extensive brain injury than was demonstrated on conventional MRI sequences. DWI with ADC mapping allowed better delineation of the extent of white matter injury.

HIE, hypoxic ischaemic encephalopathy; ADC, apparent diffusion coefficient.

^a No. of patients undergoing MRI examinations with DWI/no. of cases of inflicted brain injury.

^b Timing from admission to DWI being performed.

from the analysis to minimize interpretation errors. This enabled the full extent of the injury to be determined at an early stage.

Is there a role for follow-up CT examinations?

Four studies (Table 5) were identified reflecting data on 80 of 131 children who had follow-up CT examinations.^{19,25,27,30} Three of these^{19,27,30} were conducted when MRI was not widely available. Early follow-up CT examinations (performed at 1.5–5 days later)¹⁹ showed evolving haemorrhages and infarcts. Late follow-up CT examinations (after day 5) showed chronic changes, such as brain atrophy, chronic SDH, and hygroma. Rao et al.²⁵ from 1999 showed that follow-up CT, when performed for clinical indications, indicated oedema, intracerebral haemorrhages that were not present on the first scan, and SDH of different densities. No study was designed to compare the detection rate of repeat CT versus early MRI and DWI, however, a number of studies detailed CT examinations performed later that validated the ischaemic changes visible on the DWI.^{21,22,28}

Is there a role for high-resolution ultrasound?

Three studies addressed the role of high-resolution ultrasound in 21 children (Table 6).^{17,20,29} Jaspán et al.²⁰ highlighted the use of ultrasound in detecting SDHs and contusional tears in six children with iBI. One of these contusional tears was confirmed on a post-mortem histological examination. Serial sonography in three cases mapped the development of cerebral swelling and ischaemic damage at the site of the tears.²⁰

Chen et al.¹⁷ compared high-resolution ultrasound with CT or MRI in 13 infants where all abnormal ultrasound examinations were compared with CT or MRI findings. However, ultrasound failed to detect two posterior cranial fossa SDHs and three basal cistern SAHs that were seen with CT or MRI. Zepp et al.²⁹ detected cerebral oedema with the help of ultrasound and Doppler, although in case one ultrasound did not identify a left frontal SAH.

Discussion

This review confirms that there is a body of published evidence to support an imaging strategy of early CT followed by early MRI with DWI. It is clear that even the most conservative statistical estimate confirms that additional or evolving abnormalities will be found on MRI in one in four children with an abnormal early CT examination. This would appear to be the optimal approach to fully delineate the extent of injury, and may assist in establishing the prognosis. It is less clear at this stage which children with a normal initial CT examination should go on to MRI/DWI, and further study of this question would be valuable.

The published literature lacks large-scale diagnostic studies where all children undergo CT and early MRI/DWI, with subsequent confirmation of precise injury by surgery or post-mortem where possible, which would enable sensitivities and specificities for each technique to be ascertained. Given the inevitable challenges to researching this population of children, it is unlikely that an ideal study design would be achievable.

As this review spans a 30-year time period, inevitably the neuroimaging techniques and equipment used have evolved considerably during this

Table 5 Follow-up computed tomography (CT) examinations

Authors	Study type	Age	No. repeat CT/No. iBI ^a	Timing of Initial CT examination	Timing of follow-up CT	Additional findings (numbers of cases)
Rao et al. (1999)	Cross-sectional	<15 years	37/47	42/47 at <24 h 4/47 at 1–2 days 1/47 at 3–6 days	Unavailable	Cerebral oedema (<i>n</i> = 6), intracranial haemorrhage (<i>n</i> = 4), IVH (<i>n</i> = 3), SDH of different ages (<i>n</i> = 5), cerebral atrophy (<i>n</i> = 15), hydrocephalus (<i>n</i> = 11), cystic encephalomalacia (<i>n</i> = 7)
Feldman et al. (1995)	Case series	<38 months	14/34	N/A	1.5–5 days (3)	Evolving SDH/SAH and infarct
Sinal et al. (1987)	Case series	<20 months	12/24	N/A	2 days – 7 years (12)	SDH, SAH, Chronic SDH, hygroma, atrophy
Zimmerman et al. (1979)	Case series	<12 years	17/26	N/A	N/A	Atrophic changes, cerebral infarction

IVH, intraventricular haemorrhage; SDH, subdural haematoma; SAH, subarachnoid haemorrhage; N/A, data not available.

^a No. of patients undergoing subsequent CT examinations/no. of cases of inflicted brain injury.

Table 6 High-resolution ultrasound (US) examination

Authors	Study type	Age	No. US/ No. iBI ^a	Timing of US	Findings comparable or better than CT/MRI	Limitations
Chen et al. (2001) China	Case series	<12 months	13/13	1–3 days (acute cases) 4–10 days (subacute) serial scans 1–4 months (5/13)	Detected 20 SDHs in 10 infants and staging was possible in 15 SDHs. Showed echogenic cortical oedema in five patients.	Unable to determine two posterior fossa SDHs and three basal cistern SAHs. Limitations of staging are echogenicity of blood dependent on density of fibrin and red blood cells.
Jaspan et al. (1992) UK	Case series	<4 months	6/6	<24 h of admission to regional neurosurgery unit and at varying intervals.	Contusional tears of subcortical white matter detected.	Skull fractures, characterization and ageing of SDHs not detected
Zepp et al. 1991	Case series	<3.5 months	2/2	On admission and follow-up	Cerebral oedema on initial images and focal parenchymal defects	Did not detect left frontal SAH ($n = 1$)

SDH, subdural haematoma; SAH, subarachnoid haematoma.

^a No. of patients undergoing high-resolution US examinations/no. of cases of inflicted brain injury.

time. Therefore, the diagnostic yield from the early CT studies is likely to be lower than the more recent studies using multidetector technology. Multisection CT with multiplanar reformatting is likely to be better able to identify small SDHs and parenchymal injury than the older studies employing 5–10 mm thick sections. Surface reformatted images may also enable more sensitive detection of skull fractures and anomalies, as well as correlating these to scalp bruising. Three Tesla MRI may be better able to detect SAH and differentiate it from SDH, particularly with the greater sensitivity for susceptibility effects at the higher field strength and employment of three-dimensional fluid attenuated inversion recovery (FLAIR) sequences. DWI enables detection of cytotoxic oedema that can develop within minutes of significant hypoxic–ischaemic injury (HII), and will more accurately and sensitively detect HII than CT. Traumatic brain injury is also more sensitively evaluated by the use of varying pulse sequences and supplemented by DWI. In the subsequent subacute and early chronic phases, pseudonormalization may account for the apparent disappearance of DWI abnormalities noted by Küker et al.²¹ after 3 weeks.

It is possible that repeat CT examinations and MRI undertaken for prognostic reasons alone may have been missed by the present search strategy, as studies on the outcome of iBI were not searched for.

Recent reports of latest MRI techniques, such as diffusion tensor imaging (DTI), proton and phosphorus magnetic resonance spectroscopy

(MRS) have not been formally evaluated and remain experimental. A case of a 14-month-old infant with a reported fall was noted to have an occipital bone fracture and SDH over the right cerebral hemisphere, tentorium, and interhemispheric fissure, but showed no evidence of parenchymal changes on MRI and DWI. However, DTI demonstrated abnormalities that were later identified as parenchymal oedema on follow-up CT examinations.³¹ Two studies^{32,33} reported the use of MRS in detecting early biochemical changes in iBI, correlating metabolic abnormalities with adverse outcome. The precise role of these techniques needs to be established in larger-scale studies.

One of the most difficult issues facing clinicians is which child to investigate for suspected iBI. A separate systematic review of the clinical indicators of iBI has been conducted, estimating the probability of abuse for specific clinical features, which it is hoped will assist with this question. Clinicians face little dilemma in instigating neuroimaging in the child with overt neurological symptoms, yet some authors have suggested that children without apparent neurological signs or symptoms, although with other overt signs of physical abuse, may have intracranial injury.^{34,35} However, these studies did not merit inclusion in this review because the abuse ranking was too low³⁴ and there was inadequate detail on CT versus MRI comparison.³⁵

Although the majority of included studies in this review analysed the added benefit of MRI when the early CT was abnormal, only one study

addressed its role in the presence of a normal early CT.²³ This study included a highly selected group of cases, where the imaging was performed in a variety of centres, and where no standardisation of reporting took place. Only one image from the initial CT was reproduced. As described above, there is significant concern as to the definition of a "normal" CT examination. MRI images may also be misinterpreted. Chabrol et al.¹⁶ reported a slender subdural haematoma that was missed on the MRI of 8-month-old baby and only identified after the baby was re-admitted with fresh intracranial injuries from which he died (case 12). It is not sufficient to perform the correct test; it must also be interpreted correctly. These examples show why it is desirable that brain imaging in suspected iBI should be reviewed by radiologists with expertise in paediatric neuroradiology and who are familiar with the pattern of injury found in iBI.

No study set out to assess the optimal time for early or repeat investigations. The time interval between early CT and repeat CT (1.5 days to 7 years) varied widely, as did the time between early CT and MRI. This is an area that merits further research.

With regards to the risks associated with ionising radiation in early life, the American Academy of Pediatrics have recently considered the risks associated with CT.³⁶ The radiation dose for a CT head examination is approximately 4 mSv, which is equivalent to 200 chest radiographs. CT techniques vary greatly in radiation exposure, but result in similar image quality. Large dose reductions (up to 90% lower than adult doses) can be implemented in paediatric CT imaging without significant loss of diagnostic information. No studies have been undertaken that show a direct link to cancer. Although there is a theoretical risk of cancer, the benefits of identifying and protecting a child who has suffered from an iBI appear to outweigh this. Optimising imaging protocols, employing parameters specific to imaging in early life, and adherence to the policy of "as low as reasonably achievable" (ALARA) is advocated.

This review has highlighted the need for full neuroradiological investigation of the infant with suspected iBI. Clearly the optimal strategy at present is an early CT examination, if this is abnormal or there are ongoing concerns a MRI with DWI should also be performed. However, with improvements in imaging technology, it is hoped that prospective studies addressing the role and benefit of MRI/DWI in children with a normal early CT, and the optimal timing of MRI/DWI after early CT will be undertaken.

Appendix A

Keywords used for Child protection Neurological Injuries (CONI)

Set 1

battered child or shaken baby or battered baby
battered infant or shaken infant
child
child abuse or child maltreatment or child protection
children
inflicted brain injury or inflicted cerebral injury
inflicted traumatic head injury or inflicted traumatic brain
intentional abuse
non-accidental injury
non-accidental trauma
non-accidental trauma
physical abuse
physical abuse
shaking baby syndrome
shaking impact syndrome
soft-tissue injury

Set 2

abusive head trauma
bleeding into brain
blow to the head
brain
brain damage
brain dissection
brain disruption
brain Haemorrhages
Brain Injuries/
brain swelling
brainstem
central nervous system
cerebral
cerebral atrophy
cerebral edema cerebral injury
cervical lumbar
cervical spine injury
cervical spine neuropathology
contusion
contusional tear
cranial injury
craniocerebral trauma
craniocervical
diagnostic triad
diffuse axonal injury
dissection
encephalomalacia
encephalopathy
extracranial CNS injury

growing skull fracture
 haematoma
 head injuries
 head trauma
 Hematoma/
 Hematoma or haematoma
 hydrocephalus
 hygroma
 hypoxic-ischaemic injury
 hypoxic-ischemic injury
 impact injury
 infarction
 inflicted brain injury or inflicted cerebral injury
 inflicted traumatic head injur: or inflicted traumatic brain injur:
 intraparenchymal adj3 tear
 interhemispheric
 intracerebral bleeding
 intracerebral haemorrhage or intracerebral hemorrhage
 intracranial haemorrhage or intracranial hemorrhage
 intracranial injuries
 intraparenchymal
 intraventricular hematoma
 laceration
 laminar necrosis
 leptomeningeal cyst
 multiple skull fracture or eggshell fracture
 neurologic injury in child abuse
 neuropathology
 non-accidental head injury
 parafalcine
 parenchymal contusion, laceration
 retinal hemorrhage
 Retinal hemorrhage
 sciwora
 shaking impact syndrome
 shearing injury
 skull fractures
 spinal cord Injury without radiologic abnormality
 subarachnoid hematoma
 subdural hematoma or subdural haematoma
 subdural hygroma
 thoracic lumbar sacral
 traumatic effusions
 ventricular haemorrhage or ventricular hemorrhage
 whiplash impact syndrome
 whiplash injury
 whiplash shaken infant

Set 3

computed tomography
 CT or CAT
 diagnostic imaging

diffusion weighted imaging
 Magnetic Resonance Imaging/
 magnetic resonance imaging (MRI)
 neuro radiology
 neuroimaging
 neurologic
 neurologic examination
 plain films
 radiological imaging
 Tomography, X-Ray Computed/
 ultrasound scan
 X-rays

All Searchable Fields (AF): truncation

1. child/ or child:.af.
2. non-accidental injur:.af.
3. non-accidental trauma.af.
4. (non-accidental: and injur:).af.
5. soft tissue injur:.af.
6. physical abuse.af.
7. (inflicted brain injur: or inflicted cerebral injur:).af.
8. (inflicted traumatic head injur: or inflicted traumatic brain injur:).af.
9. (or/2–8) and 1
10. (child abuse or child maltreatment or child protection).af.
11. (battered child or shaken baby or battered baby).af.
12. (battered infant or shaken infant).af.
13. Shak: Baby Syndrome.af.
14. shak: impact syndrome.af.
15. or/10–14
16. 9 or 15
17. abusive head trauma.af.
18. bleeding into brain.af.
19. blow to the head.af.
20. Brain Injuries/ or brain damage.af.
21. (brain haemorrhage: or brain hemorrhage:).af.
22. (brain swelling or cerebral edema).af.
23. cerebral injur:.af.
24. cervical spine injur:.af.
25. cervical spine neuropathology.af.
26. cranial injur:.af.
27. craniocerebral trauma.af.
28. diffuse axonal injur:.af.
29. extracranial CNS injur:.af.
30. extracranial Central Nervous System injur:.af.
31. central nervous system injur:.af.
32. (extradural haematoma or hematoma).af.
33. extradural haemorrhage.af.
34. haemorrhagic retinopathy.af.
35. (head inur: or head trauma).af.
36. impact injur:.af.

37. intracerebral bleeding.af.
 38. (intracerebral haemorrhage or intracerebral hemorrhage).af.
 39. (intracranial haemorrhage or intracranial hemorrhage).af.
 40. intracranial injur:.af.
 41. (intraventricular hematoma or intraventricular haematoma).af.
 42. (multiple skull fractur: or eggshell fractur:).af.
 43. (neurological injur: adj3 child abuse).af.
 44. neuropathology.af.
 45. non-accidental head injur:.af.
 46. (parenchymal contusion or laceration).af.
 47. (retinal hemorrhage or retinal haemorrhage).af.
 48. skull fracture:.af.
 49. (spinal cord injury adj3 radiologic abnormality).af.
 50. spinal cord injur:.af.
 51. (subdural haematoma or hemotoma).af.
 52. (subarachnoid hematoma or subarachnoid haematoma).af.
 53. (subdural haemorrhage or subdural hemorrhage).af.
 54. (ventricular haemorrhage or ventricular hemorrhage).af.
 55. whiplash impact syndrome.af.
 56. whiplash injur:.af.
 57. whiplash shaken infant.af.
 58. infarction.af.
 59. (hypoxic-ischemic injur: or hypoxic-ischaemic injur:).af.
 60. (contusion: or contusional tear).af.
 61. Hematoma/ or (hematoma or haematoma).af.
 62. laceration:.af.
 63. shearing injur:.af.
 64. traumatic effusion:.af.
 65. subdural hygroma.af.
 66. hygroma.af.
 67. interhemispheric.af.
 68. parafalcine.af.
 69. (brain or brainstem).af.
 70. cerebral.af.
 71. intraparenchymal.af.
 72. sciwora.mp.
 73. spinal cord injury without radiologic abnormality.af.
 74. cervical lumbar.af.
 75. thoracic lumbar sacral.af.
 76. leptomeningeal cyst.af.
 77. growing skull fracture.af.
 78. hydrocephalus.af.
 79. laminar necrosis.af.
 80. encephalomalacia.af.

81. cerebral atrophy.af.
 82. craniocervical.af.
 83. encephalopathy.af.
 84. (intraparenchymal hemorrhag: or intraparenchymal haemorrhag:).af.
 85. (spinal cord injury adj3 physical abuse).af.
 86. or/17–85
 87. Tomography, X-Ray Computed/ or Computed tomography.af.
 88. (CT or CAT scan:).af.
 89. diagnostic imaging.af.
 90. Magnetic Resonance Imaging/ or (magnetic resonance imaging or MRI).af.
 91. neuroradiology.af.
 92. neuroimaging.af.
 93. plain films.af.
 94. radiological imaging.af.
 95. X-rays.af.
 96. neurologic: imaging.af.
 97. diffusion weighted imaging.af.
 98. neurologic examination.af.
 99. ultrasound scan:.af.
 100. or/87–99
 101. 16 and 86 and 100
 102. remove duplicates from 101
 103. limit 102 to yr="1970–2007"

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