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Neuropathology of inflicted head injury in children
II. Microscopic brain injury in infants

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Summary
There are very few reports in the literature dealing with the neuropathology of infant head injury, and the question of whether diffuse traumatic brain damage [diffuse axonal injury (DAI)] occurs in such children has not yet been reliably established by detailed neuropathological studies. We report the findings in the brains of a series of 37 infants aged 9 months or less, all of whom died from inflicted head injuries, and 14 control infants who died of other causes. Axonal damage was identified using immunohistochemistry for β-amyloid precursor protein. Full clinical details were available for each case, the most constant of which in the study cohort was an episode of significant apnoea at presentation, found to have been recorded in 75% of cases. Global hypoxic damage was the most common histological finding. Widespread axonal damage, interpreted as vascular, was present in 13 cases, but widespread traumatic axonal injury was found in only two children, both of whom had severe head injuries with multiple skull fractures. Epidural cervical haemorrhage and focal axonal damage to the brainstem and the spinal nerve roots, found in 11 cases but not in controls, indicate that the craniocervical junction is vulnerable in infant head injury, the neuropathology being that of stretch injury from cervical hyperextension/flexion. Damage to this region could account for the observed apnoea, which could in turn lead to hypoxic damage and brain swelling. The observation that the predominant histological abnormality in cases of inflicted head injury in the very young is diffuse hypoxic brain damage, not DAI, can be explained in one of two ways: either the unmyelinated axon of the immature cerebral hemispheres is relatively resistant to traumatic damage, or in shaking-type injuries the brain is not exposed to the forces necessary to produce DAI.

Keywords: cervical hyperextension; diffuse axonal injury; infant head injury; non-accidental head injury

Abbreviations: βAPP = β-amyloid precursor protein; DAI = diffuse axonal injury; NAI = non-accidental injury

Introduction
Clinical reviews of fatal non-accidental infant head injury, especially of the 'shaken baby syndrome', tend to emphasize a constellation of findings: little or no evidence of impact to the head, acute subdural haemorrhage, intraocular haemorrhages of various types, brain swelling and 'diffuse brain damage', often specified as diffuse axonal injury (DAI) (Caffey, 1974; Brown and Minns, 1993; Munger *et al*., 1993; Duhaime *et al*., 1998; Lancon *et al*., 1998; David, 1999). The fact that such children are unconscious on arrival at hospital, with swollen brains and markedly hypoxic parenchymal changes on CT scan, suggests that they have indeed suffered severe diffuse brain damage. However, review of the literature suggests that the scientific evidence for this being traumatic damage is scanty. We have undertaken a detailed neuropathological study of 37 infants known to have suffered inflicted head injury to see whether DAI, an entity originally described in severe acceleration–deceleration injuries in adults, does in fact occur in non-accidentally injured infants. We have then critically reviewed papers dealing with the neuropathology of microscopic brain injury in non-accidental injury (NAI), comparing our findings with those reported previously.

Methods
Study population
The study population comprised 37 cases of head injury, established to be non-accidental according to criteria described previously (Geddes *et al*., 2001). The subjects were all infants, defined as children <1 year of age. Their age

range at the time of the head injury was 20 days to 9 months (median 2.4 months, mean 3.2 months). In 28 out of 37 cases (76%), the presenting history given by the carer to the ambulance and/or hospital staff was of the child having stopped breathing, having had respiratory difficulties, or having turned blue and floppy. Four infants were said to have been found dead, three others were reportedly dropped, one was said to have fallen and one was thrown across the room. Survival ranged from 0 to 23 months (median 2.4 months, mean 3.2 months).

A control series of 14 infants who had died of other causes was also used, to determine whether any changes found in the NAI cases were present in other infant deaths. These comprised 12 males and two females, of ages ranging from 2 days to 11 months (median 3 months). The causes of death were SIDS (sudden infant death syndrome) (seven), respiratory tract infection with breathing difficulties (five), perinatal asphyxia (one) and gastroenteritis (one). All of the SIDS cases were found dead, and one of those with respiratory symptoms survived <30 min. Survival of the remaining six cases was >4 h.

The research proposal was approved by the local research ethics committee. Full documentation, including clinical histories and witness statements, was available for all cases.

Sampling for microscopy

The brains were systematically sampled for histology, and where initial sampling had been inadequate, further blocks were taken. In 21 study cases and 13 out of 14 controls, large blocks were used. In 50 out of the 51 brains (subjects + controls), minimum sampling included several blocks of hemispheric white matter, of corpus callosum, internal capsule, cerebellum, midbrain, pons, medulla and spinal cord. In the remaining brain, an NAI case, there were no blocks of the brainstem, merely cerebrum and several segments of cervical spinal cord.

Staining methods

Immunocytochemistry for β-amyloid precursor protein (βAPP) was performed on all cases, with CD68 additionally used on long surviving cases or cases in which there appeared to have been an earlier head injury. Additional routine stains such as Perls were used as required. Technical methods and the criteria used in this study for the diagnosis of microscopic brain injury (hypoxic neuronal damage and the interpretation of axonal damage) have been described in a companion paper (Geddes *et al*., 2001) (see also Fig. 1).

Literature seach

A literature search was undertaken, looking for neuropathological series describing histological findings in NAI children.

Results

Clinical details and neuropathological findings have already been reported for the study population as part of a larger series of non-accidental head injury in children (Geddes *et al*., 2001). The principal details are summarized in Tables 1 and 2; further relevant information is given below.

Microscopic axonal damage

Study group

In total, βAPP positivity in axons was detected in 25 out of 37 cases, including 11 of the 14 cases who were said to have been found dead. In 13 out of 25, the axonal pathology appeared to be largely vascular in nature, associated with brain swelling and raised intracranial pressure (Fig. 1). Five brains showed minimal traumatic axonal damage affecting only the corpus callosum or central white matter, while severe traumatic damage, widespread enough to be described as DAI (see Discussion), was present in two. Distinguishing between terminal hypoxic–ischaemic and traumatic damage to axons (Geddes *et al*., 2001) was not always easy, but in a few cases both pathologies appeared to be present. Positivity in one case could not be assessed because of the state of preservation of the brain.

In eight other cases, βAPP immunohistochemistry revealed axonal bulbs in the brainstem, anatomically localized to the corticospinal bundles on both sides of the caudal pons and medulla (Fig. 2); in seven out of eight cases this was the only axonal βAPP expression detected in the brain. In some of the cases the bulbs in the long tracts were readily detectable on haematoxylin and eosin staining, and in one a microglial reaction was present round them (Fig. 3) suggesting that they were of several days' duration (Geddes *et al*., 1997). In three further cases axonal damage was detected in the cervical spinal cord and/or dorsal nerve roots.

Control group

Two cases displayed vascular axonal damage in central white and, to a lesser extent, in deep grey matter. In one of these, a child with severe gastroenteritis, there was raised intracranial pressure caused by brain swelling. The other was a child born at 36 weeks who had severe perinatal hypoxia–ischaemia and who lived for only 2 days. There was no βAPP expression in either corticospinal tract tracts or axons in the cervical cord in any of the controls; indeed, there was no axonal damage, either recent or old, that might be interpreted as being traumatic.

Other microscopic findings

In the NAI group, severe widespread neuronal hypoxia was seen in 29 out of 37 cases (78%), of which eight had no documented survival, having been reportedly found dead. In the control group, one case, the premature child who suffered

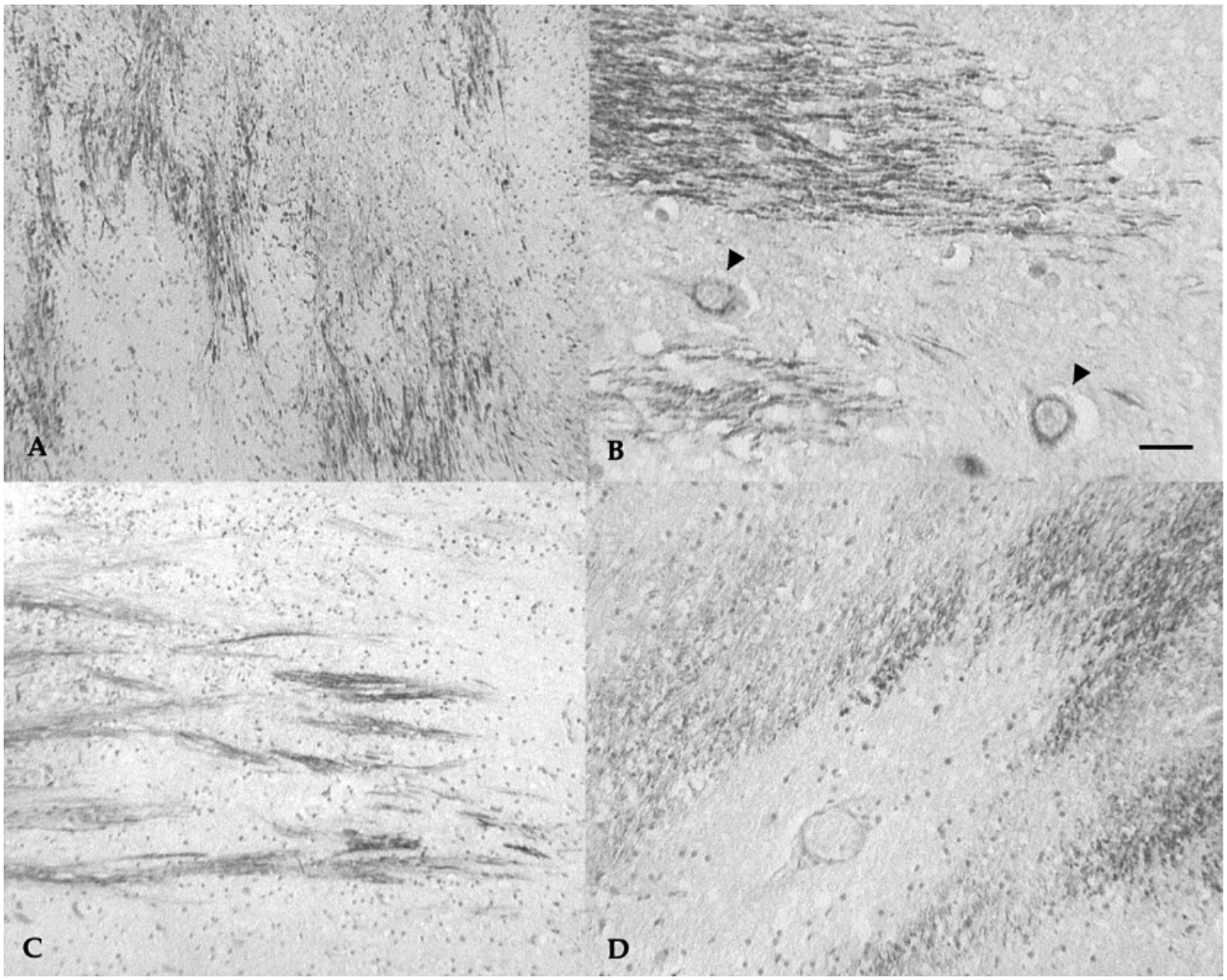

Fig. 1 Patterns of βAPP immunoreactivity interpreted as vascular, seen in three low power views (**A**, **C** and **D**) and at higher magnification in the deep grey matter (**B**). (**A**) Geographic staining, outlining areas of ischaemia in the centrum semiovale; (**B**) bundles of diffusely reactive axons running through the putamen [the two neurones in the lower half of the field (arrowheads) also show cytoplasmic expression of βAPP]; (**C**) olivocerebellar fibres just to one side of the midline in the medulla, in a grossly swollen brain; (**D**) perivascular staining. Bar = 50 μm. Reproduced with permission from Geddes and Whitwell (2001).

Table 1 *Outline details of 37 infants (<1 year) with inflicted head injury*

Factor	No. of days
Age at head injury (n = 37)	
Median	73
Mean	97
Range	20–273
Survival (n = 37)	
Median	1
Mean	27.7
Range	0–695

perinatal asphyxia, showed severe hypoxic changes. Two further NAI cases had changes throughout the brain, although of a milder degree.

Literature review

Five studies of NAI were found in which there had been a microscopic examination of the brain (Lindenberg and Freytag, 1970; Calder et al., 1984; Vowles *et al*., 1987; Shannon *et al*., 1998; Gleckman *et al*., 1999). Outline details of these papers, including the authors' principal conclusions, are given in Table 3.

Axonal damage described in the studies of Calder and Vowles (most of whose cases are the same) did not fulfil criteria for a diagnosis of DAI—by definition, damage to cerebral white matter and the upper brainstem (Adams *et al*., 1989; Adams *et al*., 1991). Shannon and co-workers found widespread hypoxia–ischaemia in their NAI cases, and concluded that altered cerebral perfusion, not trauma, was responsible for widespread axonal pathology. Localized axonal damage in the high cervical cord in their head-injured

Table 2 *Principal details of the 37 infants in this series*

No.	Sex	Age at injury (years)	History of presentation	Survival time	Significant extracranial injury	Skull fracture	Raised ICP	Acute SDH	Other significant neuropathology	Diffuse axonal injury	Vascular axonal injury	Global hypoxia–ischaemia	Evidence of neck injury*	Retinal haems.
1	F	16 weeks	Apnoea	5 days	Old rib fractures	No	Yes	Yes	Contusions; tears	No	Yes	Yes	No	Bilat.
2	M	2 months	Apnoea	None §	Old rib fractures	Yes	No	No		No	No	No	Yes	No
3	M	7 weeks	Thrown	None §	Recent fracture femur	Bilat.	Yes	Yes		No	Yes	Yes	No	No
4	M	4 months	Dropped	None	No	Bilat.	Yes	No	Contusions; tear	No	No	Yes	No	N/E
5	M	2 months	Found dead	None	No	Yes	Yes	Yes		No	No	No	Yes	N/E
6	M	20 days	Apnoea	None §	No	No	Yes	Yes		No	No	Yes	Yes	No
7	F	4 months	Apnoea	24 hours	Mesenteric bruising	Bilat.	Yes	Yes		No	Yes	Yes	No	Bilat.
8	M	2 months	Apnoea	5 months	Recent rib fracture	No	*Not at death*	No		No	No	Yes	No	N/E
9	F	2 months	Found dead	None §	Extensive bruising	No	No	Yes		No	No	Yes	Yes	Bilat.
10	F	2 months	Apnoea	2 days	No	Yes	Yes	Yes		No	Yes	Yes	Yes	Bilat.
11	M	6 weeks	Apnoea	6 days	No	No	Yes	Yes		No	Yes	Yes	No	Bilat.
12	M	5 weeks	Apnoea	2 days	Recent rib fracture	Yes	Yes	Yes		No	Yes	Yes	Yes	Bilat.
13	F	7 weeks	Apnoea	3 days	Old rib fractures	Yes	Yes	Yes		No	Yes	Yes	Yes	Bilat.
14	M	2 months	Apnoea	None §	No	No	Yes	Yes		No	Yes	Yes	No	Bilat.
15	F	5 weeks	Apnoea	23 months	No	Yes	*Not at death*	Yes		No	No	No	No	Bilat.
16	F	10 weeks	Apnoea	6 days	No	No	Yes	Yes		No	No	Yes	*No brainstem*	Bilat.
17	M	4 months	Apnoea	3 days	No	No	Yes			No	No	Yes	No	N/E
18	M	3 months	Dropped	None §	Old fractures tibia and femur	Bilat.	Yes	No	Tears	Yes	Yes	No	Yes	No
19	F	9 weeks	Found dead	None §	Ruptured liver; old rib fractures	Yes	Yes	Yes		No	No	Yes	Yes	Bilat.
20	F	3 months	Apnoea	None §	No	No	Yes	Yes		No	No	Yes	No	Bilat.
21	F	9 months	Apnoea	2 days	No	No	Yes	Yes, SOL		No	No	Yes	No	Bilat.
22	F	12 weeks	Apnoea	9 hours	No	No	Yes	Yes		No	Yes	Yes	No	Bilat.
23	F	5 months	Apnoea	2 days	No	Bilat.	Yes	Yes		No	No	Yes	Yes	Bilat.
24	M	7 weeks	Apnoea	3 days	No	No	Yes	Yes		No	Yes	Yes	No	Bilat.
25	F	5 weeks	Apnoea	6 days	Old rib fractures	No	Yes	Yes	ICH	?	?	Yes	?	Bilat.
26	F	3 months	Apnoea	2.5 months	Old fracture clavicle	No	*Not at death*	Yes	ICH	No	No	Yes	No	No
27	F	4.5 months	Apnoea	11 days	Old rib fractures	Yes	No	Yes	Tear	No	No	Yes	No	N/E
28	M	8 months	Apnoea	2 days	No	No	Yes	Yes, SOL		No	No	Yes	No	Bilat.
29	M	6 months	Fall	12 hours	No	No	Yes	Yes		No	Yes	Yes	No	Bilat.
30	M	6 months	Apnoea	24 hours	No	No	Yes	Yes		No	No	Yes	No	Bilat.
31	M	3 weeks	Apnoea	None §	No	Yes	Yes	No		No	No	Yes	No	No
32	M	6 weeks	Apnoea	None	Recent rib fractures	No	Yes	Yes		No	No	No	No	No
33	F	5 months	Apnoea	24 hours	No	Bilat.	Yes	Yes		Yes	No	Yes	Yes	No
34	F	7 months	Apnoea	None §	No	No	Yes	Yes		No	Yes	Yes	Yes	No
35	F	8 weeks	Apnoea	4 days	No	No	Yes	No		No	No	Yes	No	N/E
36	F	7 months	Dropped	3 days	Old rib fracture	Yes	No	Yes		No	No	Yes	No	Bilat.
37	M	5 weeks	Found dead	None §	No	No	Yes	Yes		No	No	No	Yes	N/E

The figures for ages at injury and survival times have been rounded up: exact ages and survival times were used for Table 1. Terms used: apnoea = any case in which the carer described the child turning blue, having breathing difficulties, gasping or stopping breathing; old = injuries antedating the terminal head injury; evidence of neck injury = axonal injury to craniocervical junction, and/or bleeding around the cord at that point. *Note that the spinal cord was not fully examined in five cases. Bilat. = bilateral; SOL = mass lesion; N/E = not examined by a pathologist; SDH = subdural haemorrhage; EDH = extradural haemorrhage; 'None §' = cases in which, on histological grounds, there had clearly been survival after an insult (see text); ICP = intracranial pressure; ICH = intracranial haemorrhage. The state of preservation of the brain in Case 25 made it impossible to assess the immunohistochemistry.

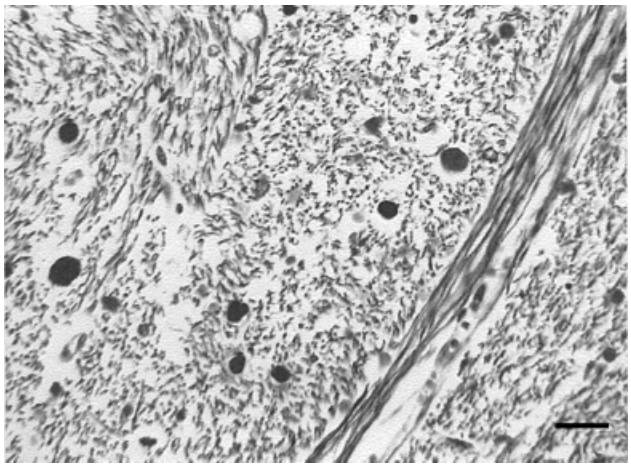

Fig. 2 A number of axonal bulbs seen in the corticospinal tract in the mid-pons in a 2-month-old boy (silver preparation). Bar = 30 μm.

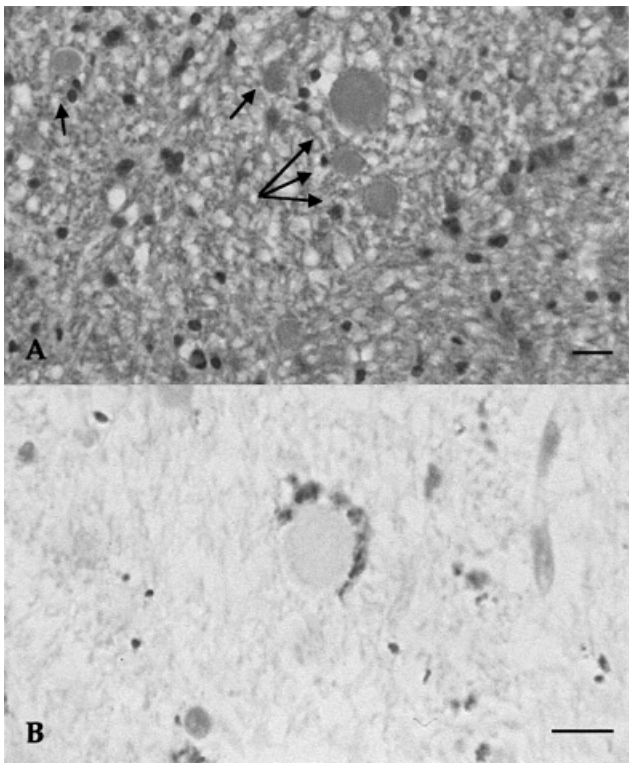

Fig. 3 (**A**) Several bulbs (arrows) are visible on a haematoxylin and eosin stain in one of the pyramids in the medulla of the same case as shown in Fig. 2. (**B**) With immunocytochemistry, a microglial reaction was seen around some of the bulbs (anti-CD68/PG-M1), suggesting that they had been present for a few days. Bars = 25 μm.

cases, also present, was attributed to trauma. Gleckman's series detected axonal damage, described as DAI, in the majority of their NAI cases. The role of brain swelling and hypoxia–ischaemia was not, however, fully addressed by this study (see Discussion).

Discussion

Head injury is a particular feature of non-accidentally injured infants, in whom it is commonly the cause of death. From a clinical point of view, the picture after inflicted head injury is quite stereotyped in severe cases: the infant arrives at hospital collapsed or moribund, having suffered an episode of apnoea or cardiorespiratory arrest, requiring resuscitation and ventilation (Johnson *et al*., 1995; Duhaime *et al*., 1998). Fundoscopic examination frequently shows bilateral retinal haemorrhages of variable severity. The principal abnormality detected by CT scan is that of a diffusely swollen hypoxic brain: the acute subdural bleeding that is almost invariably present in such cases is frequently trivial in terms of the quantity of blood in the subdural space, and rarely necessitates neurosurgical intervention (Brown and Minns, 1993; Duhaime *et al*., 1998); indeed, it may not be detected by neuroimaging (Hart *et al*., 1996; Feldman *et al*., 1997). Such a child is assumed to have diffuse brain damage which, together with brain swelling, accounts for the loss of consciousness and prolonged coma. The immediate mode of death is raised intracranial pressure.

The first reports in the literature that attempted to investigate the nature of the diffuse brain damage in NAI were two papers looking at the same cases (Calder *et al*., 1984; Vowles *et al*., 1987), the second of which by Vowles, who is one of the authors of this paper, has been widely quoted. Investigating the optimal silver method to demonstrate injury to thinly myelinated infant axons, Vowles and colleagues found axonal bulbs in six out of 10 cases and concluded that DAI occurred in inflicted infant head injury. However, the paper was published before the routine use of βAPP immunocytochemistry had made clear that there is a wide spectrum of traumatic axonal damage, from very mild to very severe, and that not all axonal injury is 'DAI' (Geddes *et al*., 2000): in their cases, lack of involvement of the brainstem would imply far less severe axonal damage (Geddes *et al*., 1997, 2000). It is difficult to make any further comment about the findings of this study, partly because the extent of sampling of the cases is not given, and partly because there is no clinical information about what are now recognized to be relevant factors—mechanical ventilation, brain swelling, raised intracranial pressure and so forth—all potential causes of axonal damage (Geddes *et al*., 2000). The papers of Calder and Vowles were the only ones on the subject for 10 years, and the idea that DAI was a feature of shaking injury became entrenched in the literature.

The question of whether DAI or lesser degrees of traumatic axonal damage occur in infant head injury is not just a matter of semantics. A diagnosis of 'DAI', which by definition is traumatic damage (Geddes *et al*., 1997, 2000), means very severe brain injury, caused by angular or rotational acceleration of high magnitude; in the context of shaking a young baby, it would imply extremely violent forces to the brain. The forces necessary to cause DAI are of such magnitude that some authors have questioned whether shaking

Table 3 *Published series dealing with microscopic findings in the brains of NAI cases*

Study	No. of cases and ages	Criteria for diagnosis of NAI?	Method for axonal damage	Widespread sampling?	Controls	Authors' principal conclusions
Lindenberg and Freytag, 1969	16 ⩽5 mo	No	Silver	Not stated	No	Contusional tears, caused by impact, characteristic lesion in infants <5 months of age
Calder *et al.*, 1984	9 ⩽3 mo[†] 3 <2 years	No	Silver	10/12	10 (no details)	1. Contusional tears in seven out of nine cases. No axonal injury in infants 2. 'White matter damage similar to that seen in adults' in the three older children
Vowles *et al.*, 1987	9 ⩽3 mo[†] 1 >4 mo[†]	No	Silver	Not stated	No	DAI in hemispheres and corpus callosum, but not in brainstem in 6/10, in association with skull fractures and contusional tears
Shannon *et al.*, 1998	11 <1 year 3 >18 mo	Yes	βAPP	'Where available'	7 HIE 6 normal	1. Hypoxic–ischaemic changes in 14/14 NAI cases 2. βAPPpositive axons in 14/14 NAI and in 6/7 HIE controls 3. βAPP-positive axons in cervical cord roots in 7/11 NAI cases
Gleckman *et al.*, 1999	10 ⩽10 mo	No	βAPP	'Usually'	7*	DAI in 5/7 shaken cases and 2/3 cases with impact; none in controls

Terms and abbreviations: widespread sampling = blocks from cerebrum and brainstem; mo = months; HIE = hypoxic–ischaemic encephalopathy. *Two controls known to have died instantly, survival time not available for two others. [†]Same cases.

alone can cause it, without some form of impact to the head as well (Duhaime *et al*., 1987). Despite this, papers and review articles on the 'shaken-baby syndrome' have tended to cite DAI as one of the inevitable and devastating sequelae of shaken-baby or 'shaken-impact' syndrome (Brown and Minns, 1993; Munger *et al*., 1993; David, 1999).

Two recent studies have used immunocytochemistry for βAPP, a sensitive marker of axonal damage (Gentleman *et al*., 1993; McKenzie *et al*., 1996), to re-address the question of axonal pathology in NAI (see Table 3). Shannon's study demonstrated widespread axonal damage secondary to hypoxia–ischaemia, as well as localized axonal damage suggestive of stretch injury to the cord, while Gleckman described the widespread βAPP expression in his cases as DAI. The principal drawback of the latter paper is that it does not properly address the question of brainstem damage due to raised intracranial pressure, because in the only control cases in which the brain was swollen, tissue sampling was inadequate: blocks of midbrain and pons, which in a swollen brain commonly express βAPP, were not available. In addition, the paper illustrates patterns of staining that we would interpret as typical of axonal damage due to brain swelling and raised intracranial pressure. This is an important criticism, for the lesson from neuropathological studies of adult head injury is that interpretation of axonal damage in cases of short survival is not easy, and requires extensive sampling using large blocks, with full clinical information (Geddes *et al*., 2000).

Our series appears to be the largest neuropathological study of non-accidental infant head injury, and we can confirm that axonal damage occurs in the brains of both head-injured subjects and in controls in much the same distribution, and with similar appearances to those described and published by Shannon and Gleckman. This is not 'DAI', but diffuse vascular or hypoxic–ischaemic injury, attributable to brain swelling and raised intracranial pressure. Despite the fact that our series of 37 infants probably includes three cases that did not survive long enough for any axonal injury to be detectable (see Results), our findings strongly suggest that severe traumatic axonal damage is a rarity in infant NAI unless there is considerable impact, and that the diffuse brain damage responsible for loss of consciousness in the majority of cases is hypoxic rather than traumatic. And while one might tend to dismiss the statements of carers in child abuse cases, the story of respiratory abnormalities or apnoea recurs with great regularity in the clinical notes of the infants. Apnoea may well be, as has been suggested by others (Johnson *et al*., 1995), an integral part of many severe cases of non-accidental infant head injury or shaken-baby syndrome. The hypoxic damage resulting from apnoea would lead to severe brain swelling, which is the usual cause of death. Such a sequence of events fits the observed clinical and neuropathological features in most NAI cases more closely than the alternative explanation that brain swelling is the result of reactive hyperaemia or deranged cerebral autoregulation. It is noteworthy that none of our control cases who were reported to have presented with respiratory abnormalities showed changes as severe as the NAI group.

So what causes apnoea and collapse in young babies who have had a head injury? One candidate would be damage to

the lower brainstem or upper cervical spine (Johnson *et al*., 1995). Infants and young children have been shown to be susceptible to high cervical cord injury without radiological evidence of bony injury, as a result of which they may suffer apnoea and cardiorespiratory arrest, or severe hypotension (Bohn *et al*., 1990). In a rather unusual study, 25% of 199 infants undergoing manipulation of the craniocervical region by a chiropractor reacted with apnoeic attacks to the stimulus (Koch *et al*., 1998). One attempt to find brainstem or high cervical cord damage in cases of NAI with MRI failed to detect abnormalities (Feldman *et al*., 1997). However, autopsy studies of NAI cases have described bleeding into paraspinal muscles, epi- or subdural haematomas at the cervicomedullary junction, and occasionally macroscopic lesions in the upper cervical cord segments (Hadley *et al*., 1989; Johnson *et al*., 1995; Hart *et al*., 1996; Leetsma, 1997; Saternus *et al*., 2000). Such reports, together with the microscopic cord findings described by Shannon (Shannon *et al*., 1998), suggest that in a significant proportion of cases the craniocervical junction can be shown to be damaged at autopsy, if carefully examined.

In their study, Shannon and his colleagues demonstrated for the first time axonal damage in the high cervical cord. They also recorded βAPP expression in a number of dorsally situated brainstem tracts, in both shaken infants and hypoxic–ischaemic controls. In our cases, we too saw foci of ischaemic-type staining in the dorsal brainstem, particularly the lower medulla, in both NAI cases and controls. However, the staining in the corticospinal tracts was quite distinct, affecting variable numbers of axons in these fibre bundles bilaterally, and appeared to represent localized traumatic axonal injury at the craniocervical junction. We believe that this pattern results from non-disruptive stretch injury to the neuraxis. Corticospinal tract damage has been suspected in cases of adult cervical hyperextension injury (Riggs and Schochet, 1995), and demonstrated in a few cases which have been neuropathologically examined, where the corticospinal fibres in the pons and medulla were preferentially involved (Lindenberg and Freytag, 1970; Hardman, 1979; Geddes *et al*., 2000). The mechanism has been discussed in some detail by Lindenberg, who drew attention to clinical signs resulting from stretching of corticospinal tracts in hyperextension injuries, particularly at the level of the pyramids (Lindenberg and Freytag, 1970).

The anatomical features that make head injury in infants biomechanically unique are well known. The immature skull is pliable, not rigid, and the conditions necessary to fracture it will be different from those in older subjects (Lancon *et al*., 1998). High head : body ratio means that in a very young baby a large mass is pivoted by the neck. Underdeveloped neck muscle tone and an inherently elastic spinal column, in which the juvenile arrangement of facet joints and upper cervical vertebral bodies renders the cord particularly vulnerable to both flexion and extension injuries, are also important factors (Kriss and Kriss, 1996). Although mechanisms of shaking must vary (Jones, 2000), and nobody really knows how babies are injured, it may not be necessary to shake an infant very violently to produce stretch injury to its neuraxis. It is true that the more vigorous the shaking, the greater the stretch that would take place at the extremities of movement, and the worse the damage produced. In all of our cases in which there was axonal pathology at the craniocervical junction, the damage was survivable; what was life-threatening was the hypoxic injury and brain swelling that resulted. Seen from this point of view, the debate over shaken versus shaken–impact becomes irrelevant, and because there is no DAI it is possible that the severe acceleration–deceleration injury that is so often cited does not in fact occur in shaken-baby syndrome. We have discussed elsewhere (Geddes *et al*., 2001) the fact that subdurals in infants are strikingly different from those in adults, who do not commonly get retinal haemorrhages with a head injury. This discrepancy, together with the lack of widespread microscopic damage due to trauma, suggests that beliefs about the conditions that produce these haemorrhages in infants, inferred as they often are from adult head injury, require fresh examination.

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