Available online at www.sciencedirect.com
SCIENCE DIRECT®

Forensic Science International 151 (2005) 71–79

Forensic Science International

www.elsevier.com/locate/forsciint

Shaken baby syndrome: A biomechanics analysis of injury mechanisms

Faris A. Bandak *

Department of Neurology, A1036 F. Edward Hébert School of Medicine, Uniformed Services, University of the Health Sciences, 4301 Jones Bridge Road, Bethesda, MD 20814, USA

Received 2 November 2004; received in revised form 2 February 2005; accepted 8 February 2005

Abstract

Traumatic infant shaking has been associated with the shaken baby syndrome (SBS) diagnosis without verification of the operative mechanisms of injury. Intensities for SBS have been expressed only in qualitative, unsubstantiated terms usually referring to acceleration/deceleration rotational injury and relating to falls from great heights onto hard surfaces or from severe motor vehicle crashes. We conducted an injury biomechanics analysis of the reported SBS levels of rotational velocity and acceleration of the head for their injury effects on the infant head-neck. Resulting forces were compared with experimental data on the structural failure limits of the cervical spine in several animal models as well as human neonate cadaver models. We have determined that an infant head subjected to the levels of rotational velocity and acceleration called for in the SBS literature, would experience forces on the infant neck far exceeding the limits for structural failure of the cervical spine. Furthermore, shaking cervical spine injury can occur at much lower levels of head velocity and acceleration than those reported for the SBS. These findings are consistent with the physical laws of injury biomechanics as well as our collective understanding of the fragile infant cervical spine from (1) clinical obstetric experience, (2) automotive medicine and crash safety experience, and (3) common parental experience. The findings are not, however, consistent with the current clinical SBS experience and are in stark contradiction with the reported rarity of cervical spine injury in children diagnosed with SBS. In light of the implications of these findings on child protection and their social and medico-legal significance, a re-evaluation of the current diagnostic criteria for the SBS and its application is suggested.

Keywords: Injury; Infant; Shaken; Baby; Rotational; Acceleration/Deceleration; Syndrome; Neck

1. Introduction

Shaking an infant to the point of severe brain injury is usually associated in the literature with the diagnosis referred to as the shaken baby syndrome (SBS). Infant shaking is in fact a potentially very injurious mechanical event. Consequently, its analysis and assessment requires knowledge and training in *Injury Biomechanics*. This scientific discipline deals with the mechanical damage processes and causations of injury. Therefore, Injury Biomechanics is central to the study of the mechanisms of injury in the SBS.

The current description of the SBS in the literature evolved over a period of nearly a half a century with some reports attributing its genesis to Caffey [1–3] a pediatric radiologist, who had the notion that an association between chronic subdural hematoma and long bone fracture in children should be a red flag for child abuse. Caffey's notion remained less known for about 10 years until he encountered the case of Virginia Jaspers, a nurse caretaker who confessed

* Tel.: +1 301 299 7357.
E-mail address: fbandak@usuhs.mil.

0379-0738/$ – see front matter
doi:10.1016/j.forsciint.2005.02.033

Table 1
Head injuries in the infant vs. the adult

Infant	Adult	Both
Deformation based		
Tears in subcortical white matter	Epidural hematoma	Lesions in the corpus callosum and brain stem
Separation of a suture	Basilar skull fractures	Traumatic axonal injury
Suture-to-suture linear fractures	Diffuse axonal injury	Linear skull fractures
Ping pong fractures		
Bilateral skull fractures		
Pressure based		
Coup hemorrhages	Coup and contre-coup hemorrhages	
Coup contusions	Coup and contre-coup contusions	
Coup acute subdural hematoma		
Relative motion based		
		Acute subdural hematoma[a]
		Localized intracranial hemorrhages[a]

[a] Represents different biomechanisms for the infant and adult.

to shaking a 2-week-old infant who died. Jasper's confession is a legalistic characterization and thus did not provide scientific support for Caffey's notion but did help start the use of the SBS label in the literature. It is unclear from the literature that Caffey envisioned this label to evolve into the SBS diagnosis as seen and applied today.

Kempe [4] contributed to the current description of SBS by introducing the ''Battered Child Syndrome'' and the concept that inconsistency between clinical observations and reported event history should signal abuse. However, a fundamental element of the meaning behind accurate ''history'' has to do with the biomechanical causes of injury. Clearly, the assessment of the mechanical causation of injury requires training and experience in Injury Biomechanics, a distinct discipline not taught in medical school. Lack of education and experience in Injury Biomechanics, amongst other factors, has led in practice to the proliferation and propagation of inaccurate and sometimes erroneous information on SBS injury mechanisms in the literature.

Another factor was added by Guthkelch [5] who synthesized the accumulating SBS medical literature to conclude that it is possible to infer shaking without impact as a cause of injury when an infant presents with subdural hematoma and retinal hemorrhages. He did not conclude that only shaking could cause such injuries. At this point in its evolution, the SBS began to develop in the literature into the *injury causation signature* that is widely described and used today. More specifically, an infant presenting with, at a minimum, acute subdural hematoma (ASDH) and retinal hemorrhages with ''inconsistent'' or ''un-explained'' biomechanical history is commonly diagnosed with SBS. Such diagnosis puts the physician in the difficult position of evaluating injury causation to determine if the reported history is biomechanically ''consistent'' or ''explainable'' without the benefit or even availability of an Injury Biomechanics assessment.

In this study, we will present a biomechanics analysis of infant shaking and its consequences on the head-neck to determine if it is possible for the fragile infant neck to withstand SBS-defined levels of head accelerations without injury.

2. Biomechanical classification of head injury

The SBS diagnosis has been primarily linked to injuries of the head. Table 1 shows the types of head injuries occurring in infants and adults. Generally, head injuries can be classified in groups with similar biomechanical genesis (Fig. 1). Biomechanical forces acting on the head can be dynamic or static (Fig. 1) and since shaking is a dynamic event, static forces (Fig. 1) will not be discussed here. Dynamic head loadings are categorized as either contact or non-contact meaning direct loading to the head and head loading through the neck respectively. The mechanical features leading to a particular head injury or set of injuries distinguishing primary and secondary are shown in Fig. 1. Primary injuries are those caused directly by the mechanical insult and secondary injuries result as that part of the pathophysiological progression following primary injury. *The boundary between primary and secondary injury in SBS has not been clearly defined.*

Fig. 1 shows injuries that have been related in the literature to local intracranial brain motion, gross intracranial brain motion, or both. For instance, a direct impact to the head resulting from a fall on a flat, hard surface produces a local indentation of the skull impinging on the brain and producing local brain deformations and pressures. Another consequence of the contact is the stopping of the moving head. The stopping force is communicated to the brain through a local path starting first with the area of contact on the scalp over the skull through the subarachnoidal cerebro-spinal fluid (CSF) layer surrounding the brain and eventually reaching the brain. The higher the fall, the faster, to a practical limit, the head impact velocity, and so the

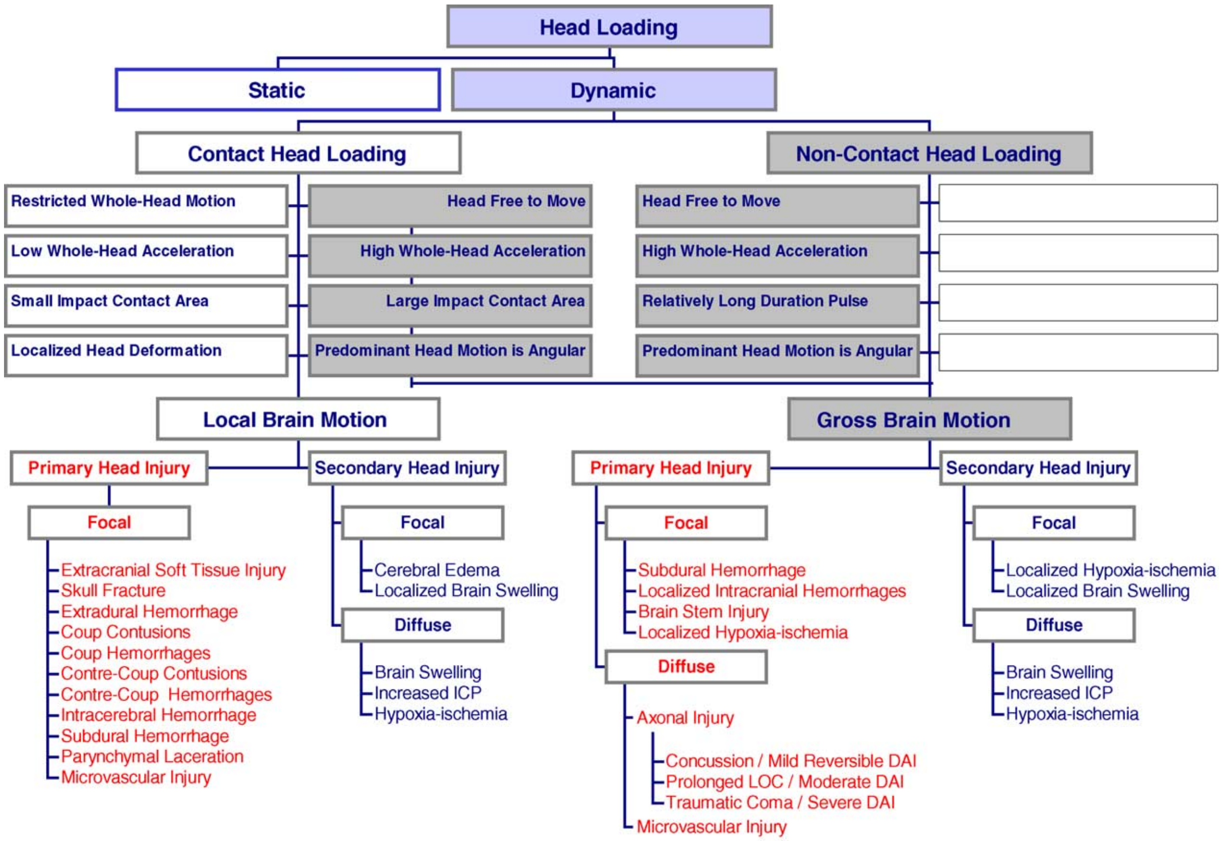

Fig. 1. Biomechanical classification of head injuries.

greater and faster the stopping force transmission to the brain. Whole-brain movement is eventually stopped against higher intracranial coup pressure and lower contre-coup pressure. The extent of gross intracranial brain movement also depends on how much rotational energy is involved in the impact [6]. Forces on the head through the non-contact mechanism pass through the neck and therefore inherently have a rotational component though, practically, much lower peak accelerations and much longer durations are achievable through this type of loading. Theoretically, injuries associated with rotational head accelerations are common to both the contact and the non-contact categories (Fig. 1) if sufficient magnitudes and rates are reached. Head injuries from non-contact loading are producible through contact loading but the converse is generally not true.

The non-contact form of head loading has been the cornerstone of the Shaking Baby Syndrome definition. In its purest form the SBS, as described in the medical literature [7], represents rotational head accelerations from a sequence of mechanical events paraphrased as follows:

An infant is gripped by the chest or shoulders and forcefully shaken back and forth whipping the head in the antero-posterior direction. The nearly non-existent muscle strength of the infant neck makes the head highly susceptible to high head-whipping rotational acceleration so severe that the brain moves relative to the interior surface of the skull resulting in torn bridging veins and so acute subdural hematoma.

While SBS has taken on other labels in the literature adding or substituting terms like ‘‘whiplash’’ and ‘‘impact,’’ it still maintains the shaking component as the central causation substratum of this diagnosis.

3. Biomechanical aspects of the infant anatomy

Discussion of infant shaking calls for a brief overview of the infant anatomy deemed relevant to the biomechanics of shaking. The head of the infant, weighing up to one third of the total body weight, is effectively a nearly unsupported mass. As a practical matter of common safety, caution is required of a caretaker when picking up or generally moving an infant. Caretakers must provide head support to compensate for the fragility, laxity, and the lack of infant neck muscle strength since it provides minimal resistance to any externally induced relative motion between the head and the thorax.

The massive-head and weak-neck attributes of the infant create the potential for severe neck injury under certain dynamic conditions. The flat, shallow, articular surfaces, cartilaginous nature, and incomplete ossification of the cervical vertebrae increases the potential for relative displacement between vertebrae and puts more burden on the weak infant cervical spine ligaments and on the infantile spinal cord. The neck as a whole, with the characteristics described above can stretch significantly beyond subluxation limits without ligamentous rupture. In addition, it can be stretched more than the spinal cord is able to accommodate [8] thus potentially injuring the spinal cord under distraction forces. Atlanto-axial and atlanto-occipital dislocation, dens fractures, and cord transections can occur from excessive stretch of the neck as has been reported for circumstances of breech extraction deliveries [9]. The infantile ligaments control the articulation and govern the mobility and range of motion of the cervical spine. These ligaments are vital to the stability of the atlanto-occipital joints governing the articulation at the cranio-vertebral junction. The cranio-vertebral junction houses the cervico-medullary portion of the spinal cord and thus presents a vulnerability to commonly fatal craniospinal injuries under serious traumatic excursions into the spinal canal. This canal is large in C1 compared to the segments below. It is occupied equally by the dens and the cord both taking up two thirds of the space with the remaining one third free space. Consequently, there is some room for the cord to move under atlanto-occipital displacement. However, displacements exceeding the available free space can injure the cord.

The chest of the infant is defined in the SBS literature as a possible grip area for the shaker. The infant's thin thoracic wall and the cartilaginous elastic nature of the ribs make the chest more vulnerable to large deformations and chest indentations which can cause injury and affect internal organs. The chest circumference is generally smaller (0.5 in. or so) than the head circumference at birth with its value reaching that of the head circumference at about 1 year of age. The neonatal chest is nearly circular and slowly becomes elliptical with age making it wider in the coronal plane at about 6 months of age. The location of the heart in an infant is of course different from that of the older child. It is located at the midpoint between the head and the buttocks and after the fourth year, the heart descends downward as the thorax grows. The chest prepares biomechanically for this descent by becoming very bony with ossified ribs forming the protective rib cage, which also descends downward providing similar protection for the kidneys, the spleen, and other organs.

Integrated into the chest structure is the thoracic part of the vertebral column. The infant spinal column has a single curve composed of the thoracic, the cervical, and the lumbar portions of the column [10]. This important feature is relevant to the infant's biomechanical response to shaking versus that of the older child. The lower portion of the spinal column, referred to as the sacral region, forms another but smaller curve. The vertebral column eventually assumes the familiar S-shape as the skeletal structure develops and the pelvis tilts forward creating the thoraco-lumbar inflection point in the familiar S-shape.

4. Injury biomechanics analysis of infantile SBS

In order to evaluate the operative injury mechanisms in the brain of an infant under SBS-defined head acceleration,

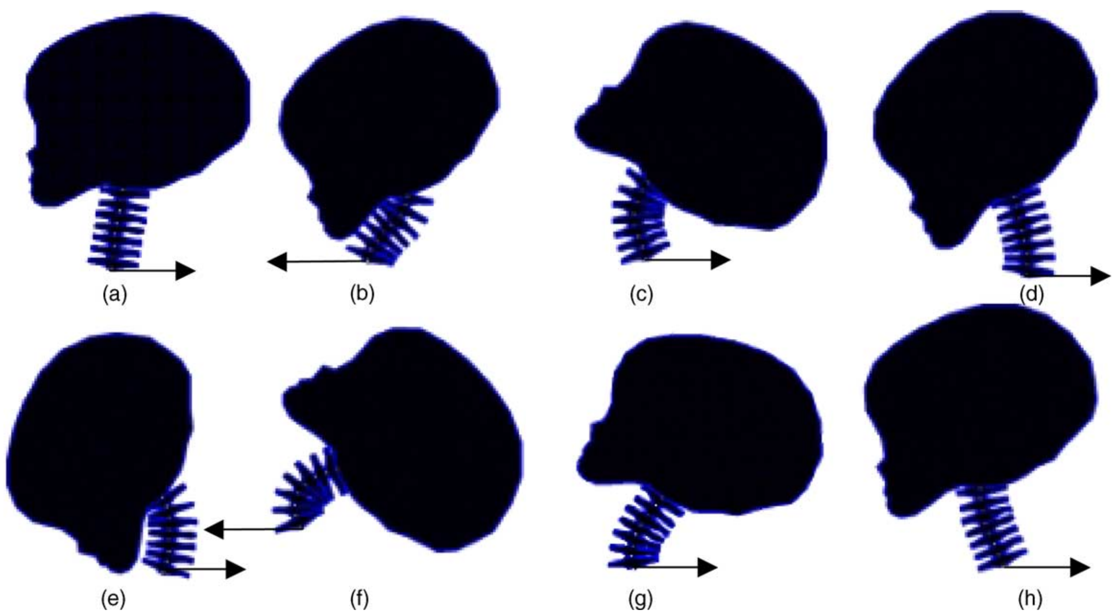

Fig. 2. Several time-history snap shots of the head-neck during chest shaking.

we must obtain the loadings that actually reach the brain along the path starting at the grip points of the shaker's hands, through the thorax, spinal column, neck, and eventually the head. Fig. 2 shows, schematically, the back and forth head motion resulting from shaking. The grip forces act on the thorax and load the ribs. They are transmitted through the posterior joints connecting the ribs to the thoracic spinal column and so shake the column imposing that back-and-forth on the base of the cervical spine portion of the spinal column. The resulting forces enter the neck at C7. We did not address possible injury to any part of the body below C7 in this study. This conservative position was taken even though the required chest-shaking intensity of SBS can cause injuries in the infant below C7.

5. SBS head loading

We have necessarily described SBS in terms of head loading because the head has been central to the definition of the SBS injuries. Chest shaking forces reach the head through the neck starting at C7 and moving back and forth in wave fashion (Fig. 2) eventually transmitting forces to the cranio-vertebral junction. Along this path, the force acts on soft, flat, incompletely ossified vertebrae, and soft ligaments. The forces reach the cranio-vertebral junction and induce the infant skull to move back and forth with little resistance to pivot about the atlanto-occipital joint. The overall head motion is governed by the neck which significantly influences the head trajectory and the center of rotation. In fact, the neck must completely bear the load that keeps the head and thorax from separating. For the infant, this type of chest-shaking head motion can be thought of as a kind of "dragging" motion where the neck, acting as a tether, pulls the unsuspecting head in response to the induced motion of the chest. This has not been described as the mechanism for SBS.

To understand what has been described in the literature for SBS accelerations, consider an illustrated example of a sphere with mass m connected to a rod with length r as shown in Fig. 3. If point B starts to move in a straight line in the horizontal direction, a force from the rod will act on it to cause it to also move inwards in the radial direction resulting in the composite, familiar motion along a circular arc ultimately setting mass m in rotation about point A. At any point along the arc, one can evaluate the acceleration of mass m. This acceleration has two main components, a tangential component (along the arc), a_t, and a normal (in the radial direction) component, a_n, as shown in Fig. 3. The figure shows that the mass is tending to escape the circular arc and go free but is constrained by the rod to move along the arc. Naturally then, the mass m is exerting a force with components $F_n = ma_n$ and $F_t = ma_t$ on the rod. If for instance, the outward acceleration a_n has a magnitude of 50 G and the value for mass is 1.36 kg, then the force acting on the rod is equal to 665 N (150 lbf). Clearly, the rod will give way if it is not strong enough to bear such a force. Under similar circumstances the neck experiences forces as the massive head is accelerated.

$a_n = v^2/r$	Normal acceleration (velocity squared over the radius)
$a_t = r\,(d^2\theta/d^2t)$	Tangential acceleration (radius times the angular acceleration)
$F = ma$	Newton's Second Law (mass times acceleration)
$F_n = ma_n$	Normal Force (distraction force)
$F_t = ma_t$	Tangential Force (shear force)

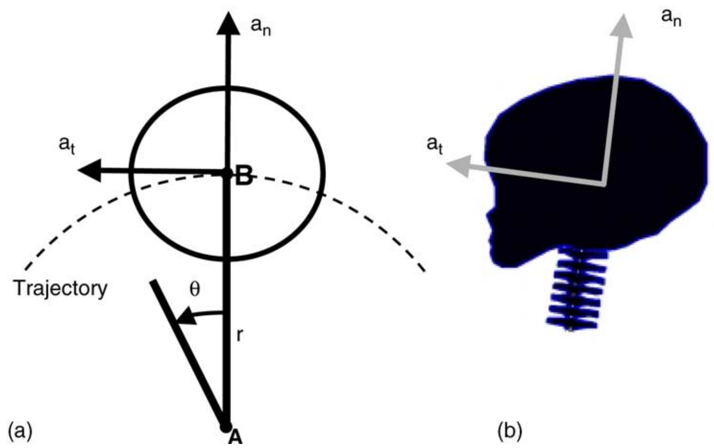

Fig. 3. Force diagram on (a) sphere and (b) head-neck schematically indicating rotational head motion about point A.

The reported SBS back-and-forth head motion of this type along an arc produces an exchange between a_n and a_t in a periodic fashion reaching peaks at alternating times along the arc. Relating these to forces acting on the rod, we see that the rod has to resist forces tending to both stretch and bend it. While more complicated biomechanically, the actual shaking response of the infant head also imposes shear and tensile forces as well as compressive forces on the infant neck.

To evaluate the neck forces produced by SBS-type head accelerations, we considered the range of rotational head acceleration and velocity levels cited in the literature. Jenny and co-authors [11] attempting to show that higher accelerations can be achieved by human manual shaking reported that peak rotational accelerations of 6000–13,252 rad/s^2 and rotational velocities of 120–153 rad/s are possible through the manual human shaking of a dummy surrogate representing a Japanese infant. Spivack used the work of Duhaime et al. [12] relating rotational velocities of 50–120 rad/s and approximately 30,000-rad/s^2 rotational acceleration to SBS. SBS is cited in the literature as having forces that are as great as those of falls from great heights, by some accounts more than 9 m (30 ft), onto hard surfaces or from high-speed motor vehicle crashes [13]. These contentions of SBS load levels have not been substantiated biomechanically with some reports refuting their validity at all [12,14].

To illuminate and compare simplified head motion energies of familiar events such as car crashes, biking, walking, etc., with shaking, we calculated the free head velocity associated with each event as shown in Table 2. The table reflects conservative but realistic estimates of maximum free head velocity for each of the events. Ironically, the values show that shaking head velocity is less than the maximum free-fall velocity from height of 1 m (3(1/4) ft). This comparability of energies raises further questions concerning the forces reported for SBS and might account in part for the misconceptions and controversial views on the head injury severity of ‘‘short falls.’’ The energy from velocity is called kinetic energy and we refer to it here as *unrealized* damage energy meaning it can be converted to potentially damaging energy through a rapid change in magnitude and/or direction. For the case of the infant head, this velocity change can come from the action of the neck on the head during chest shaking as we explained earlier or it can come from an impact action applying force directly on the head such as that from a fall. Table 2 shows the energies as multiples of units of failure energy where the failure energy was taken to be equal to the skull fracture energy in the infant. Skull fracture energy was chosen since skull fracture has been used as a conservative indicator of impact intracranial injury in infants [15,16].

A range of angular accelerations and velocities was taken to be between 5000 and 15,000 rad/s^2 for rotational acceleration and between 50 and 150 rad/s for rotational velocity. This range was chosen because it is conservatively representative of the *lower* values cited in the literature for SBS and reported to be below thresholds postulated in the SBS literature for subdural hemorrhages. The SBS forces were obtained and compared with the current biomechanical data related to infant injury thresholds.

6. Results and discussion

The shaken baby syndrome, as a diagnosis, has become virtually synonymous with inflicted cerebral trauma. The injury mechanisms of the SBS have historically not been linked to cervical spine injury even though its early evolution was bolstered by Caffey's [3] interpretation of Ommaya's whiplash work [17,18]. Caffey interpreted this work as a demonstration that brain injury could occur from head whipping by chest shaking without contact head impact. Caffey translated Ommaya's results without considering Injury Biomechanics, into an explanation for a confession of shaking.

The Ommaya whiplash animal model primarily addressed the primate head as an adequate surrogate for the adult human brain under the types of loading tested. While an argument can be made for this model substitution for the case of adult human head, the neck is another matter. Astonishingly, Caffey did not give consideration to the head-neck features of the primate model used to study whiplash. In fact, the animal model used had quite opposite whiplash-related features compared to the infant when the head-neck is concerned. Specifically, the rhesus monkey has a small,

Table 2
Head velocities and normalized failure energy associated with familiar dynamic events compared with shaking and falls

	Height (m)	Velocity (m/s)	Normalized impact energy (Nm/N)	1.3 N head weight (E_{SF})[a]	2.3 N head weight (E_{SF})
Free fall (30 ft)	9.10	13.36	9.10	13.00	23.00
Powered vehicles 48 km/h (30 mph)		13.36	9.10	13.00	22.99
Adult biking 32 km/h (20 mph)		8.90	4.04	5.77	10.20
Adult running 24 km/h (15 mph)		6.70	2.29	3.27	5.78
Toddler biking 16 km/h (10 mph)		4.40	0.99	1.41	2.49
Toddler running 9.7 km/h (6 mph)		2.70	0.37	0.53	0.94
Free fall (3 ft)	0.91	4.09	0.85	1.22	2.15
Shaking 11–15.5 km/h (6.8–9.5 mph; 10–14 ft/s)		4.31	0.95	1.35	2.39

[a] E_{SF} is the energy associated with skull fracture and so the column is in units of E_{SF}.

Table 3
Neck distraction forces vs. head weight and center of rotation

Neck distraction force (N)						
Head weight (kg)	0.68		1.34		1.59	
Neck length (cm)	3.81	6.35	3.81	6.35	3.81	6.35
Low end of reported SBS rotational acceleration range	1027	1711	1711	2852	2395	3992
High end of reported SBS rotational acceleration range	9240	15399	15399	25665	21559	35931

relatively less massive, head on quite a strong neck while the infant on the other hand has a relatively more massive head on a floppy, weak, neck. Consequently, the infant neck is far more susceptible to whiplash injury than that of the rhesus monkey under the similar chest-shaking head accelerations. Nearly half of the concussed animals in Ommaya's [17] whiplash experiments experienced cervical spine or brain stem injuries even with the disproportionately strong neck relative to the human infant.

Ommaya's experiments [17] as well as follow-up primate experiments by Ommaya's previous co-workers, Gennarelli and Thibault [19] supported a rotational acceleration

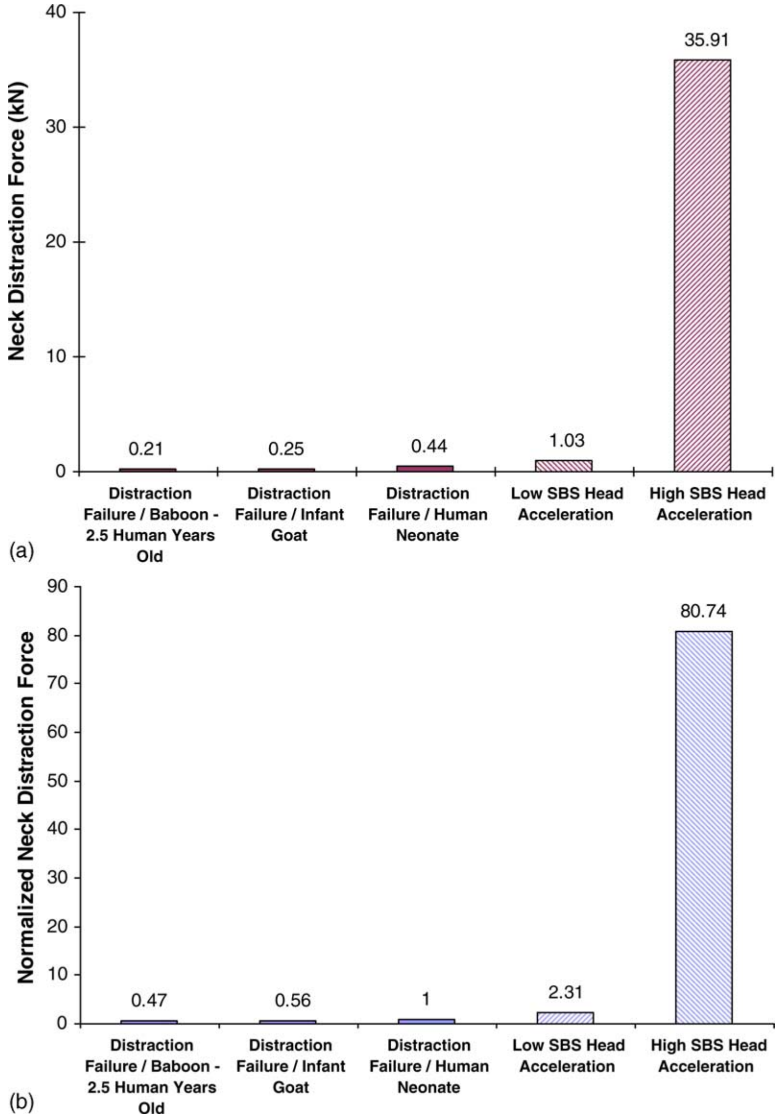

Fig. 4. SBS neck distraction force vs. (a) Structural failure of the cervical spine and (b) normalized to human neonate distraction failure data.

mechanism for the generation of cranial subdural hematomas. This is the much-heralded differential rotational skull-brain motion mechanism that causes parasagittal bridging veins to rupture and thus hemorrhage below the dura. This mechanism was postulated for the adult head with a fully ossified, stiff, skull which plays a major role in its activation. It is important to note that the Gennarelli-Thibault experiments were conducted in a way that protected the neck from head whipping forces. In those experiments, the head of the primate was potted in a metal cylinder which was constrained to accelerate and then decelerate along a prescribed arc in a prescribed time frame. In this way, the neck was not subjected to the forces of the accelerated free head as it would be if the loadings were applied at the chest. This is precisely and erroneously the presumed SBS head motion where equivalent rotational accelerations of the infant human head were calculated by scaling this type of data. The important question when using the results of these experiments to interpret infant shaking injury is whether it is naturally possible for a free human head to reach such head accelerations through chest shaking without neck injury. This question was not addressed by those primate experiments nor has it been addressed quantitatively in the literature. It was addressed in this study for the case of infant shaking.

Our results for SBS head accelerations imposed for different head masses and centers of rotation (Table 3) representative of infants show that the resulting forces produce both distraction and localized hyper-flexion and hyper-extension forces on the infant neck and that these forces increase with increasing head mass. Therefore, it can be concluded that for the same acceleration and same neck size, a heavier head is more likely to produce a shaking neck injury.

Using a range of values for head mass and center of rotation for infants, and peak acceleration and peak velocity for SBS, we obtained neck distraction forces ranging from a lower bound of 1027 N to an upper bound of 35,910 N (Table 3). These values were compared with experiments on several animal species and on neonate cadavers as shown in Fig. 4. The experimental results show that the cervical spine becomes susceptible to severe injury at values as low as 209 N for the baboon at 3 years equivalent human age [20,21]. Fig. 4 shows failure values of 249 N for the infant goat neck [22] and 445 N for the human neonate neck [9]. It is important to note that these experimental values approximate force levels that would cause major structural failure of the cervical spine for each species. Serious cord injury or even transection can be expected to occur at even lower force levels [8]. The important observation here is the order of magnitude differences between what is reported in the SBS literature as necessary levels to cause injury and the actual magnitudes of the operative forces.

These force levels conservatively indicate that severe cervical spinal cord or brain stem injury in the infant can occur at significantly lower levels than invoked by the current SBS literature as a cause of subdural hematomas. These results are quite consistent with the laxity and fragility of the infantile cervical spine and the lack of muscle strength of the neck. They are also consistent with the established experience that neck injury does not usually occur as a result of direct loading to the neck. The more common causes of neck injury are by action that involves the head. Whether by direct head impact induced accelerations, or head accelerations from indirect chest shaking, it is generally the forces on the head that transmit to neck injury forces. This is the essence of the term "whiplash" that is quite familiar to neck injury victims of rear-end motor vehicle crashes. Ironically, whiplash has been intrinsically embraced in the definition of the Shaken Baby Syndrome without reference at all to cervical spine injury.

7. Conclusions

This study resulted in the following findings:

1. Head acceleration and velocity levels commonly reported for SBS generate forces that are far too great for the infant neck to withstand without injury.
2. Head velocity from human manual shaking is of the same order as free fall head velocity from a height of about 1 m (approximately 3-ft).
3. Shaking head accelerations can potentially cause severe, if not lethal, cervical spinal cord or brain stem injury in the infant at levels *well below* those reported for the Shaking Baby Syndrome.
4. Given that cervical spine injury is reported to be a rare clinical finding in SBS cases, the results of this study indicate an SBS diagnosis in an infant with intracerebral but without cervical spine or brain stem injury is questionable and other causes of the intracerebral injury must be considered.
5. Re-consideration and clarification of the relative significance of each of the terms "shaking" and "impact" as used in the SBS diagnosis of cerebral trauma in an infant is warranted.
6. Cervical spine and/or brain stem injury should be included amongst the factors considered in the determination of consistency of reported history in cases where infant shaking is suspected. It should be kept in mind that such injury is not exclusive to shaking as the sole mechanical cause. Traumatic shaking is just one of the causes.
7. The rotational head acceleration mechanism for the intracerebral injuries of the SBS is inconsistent with the findings of this study. A non-impact, shaking-only, mechanism of primary intracerebral injury in an infant has not yet been described and requires further research. We have shown that infant shaking can cause primary brain stem or cervical spinal cord disruption which is known to lead to secondary intracerebral injury manifest-

ing as the familiar apneic presentation which is followed by hypoxic-ischemic response and cerebral edema.

In light of the findings of this study, re-evaluation of the present diagnostic criteria for the SBS merits serious attention for its implications on child protection and for the social and medicolegal significance of its application.

References

[1] J. Caffey, Multiple fractures in the long bones of infants suffering from subdural hematoma, Am. J. Roentgen. 56 (1946) 163.
[2] J. Caffey, On the theory and practice of shaking infants: its potential residual effects of permanent brain damage and mental retardation, Am. J. Dis. Child. 124 (1972) 161.
[3] J. Caffey, The whiplash shaken infant syndrome: manual shaking by the extremities with whiplash- induced intracranial and intraocular bleedings, linked with residual permanent brain damage and mental retardation, Pediatrics 54 (1974) 396–403.
[4] C.H. Kempe, F.N. Silverman, R.F. Steele, W. Droegemueller, H.K. Silver, The battered child syndrome, JAMA 181 (1962) 17–24.
[5] A.N. Guthkelch, Infantile subdural hematoma and its relationship to whiplash injuries, Br. Med. J. 2 (1971) 430–431.
[6] F.A. Bandak, On the mechanics of impact neurotrauma: critical review and synthesis, In: Bandak et al., (Ed.),Traumatic Brain Injury: Bioscience and Mechanics, Mary Ann Liebert, 1996, pp. 139–153.
[7] American Academy of Pediatrics, Committee on child abuse and neglect, Shaken baby syndrome: Rotational cranial injuries – technical report, Pediatrics, 2001 108, 1, 206–210.
[8] W.E. Stern, R.W. Rand, Birth injuries to the spinal cord: report of two cases and review of the literature, Am. J. Obstet. Gynecol. 78 (1959) 498.
[9] M. Duncan, Laboratory note: on the tensile strength: a critical of the fresh adult fetus, Br. Med. J. 2 (1874) 763–764.
[10] W.H. Johnson, J.A. Kennedy, Radiographic Anatomy of the Human Skeleton, Williams and Wilkins, Baltimore, 1961.
[11] C. Jenny, T. Shams, N. Rangarajan, T. Fukuda, Injury Biomechanics Research, 30th International Workshop, Ponte Vedra Beach, Florida, 2002, pp. 129–143.
[12] A.-C. Duhaime, T.A. Gennarelli, L.E. Thibault, D.A. Bruce, S.S. Margulies, R. Wiser, The shaken baby syndrome: a clinical, pathological, and biomechanical study, J. Neurosurg. 66 (1987) 409–415.
[13] A.C. Duhaime, J. Alario, et al. Pediatrics 90 (1992) 179–185.
[14] M.T. Prange, B. Coats, A.C. Duhaime, S.S. Margulies, Anthropomorphic simulations of falls, shakes, and inflicted impacts in infants, J. Neurosurg. 99 (2003) 143–150.
[15] S.A. Schutzman, P. Barnes, A.-C. Duhaime, D. Greenes, C. Homer, D. Jaffe, R. Lewis, Evaluation and management of children younger than 2-years-old with apparently minor head trauma: proposed guidelines, Pediatrics 107 (5) (2001) 983–993.
[16] K. Quayle, D. Jaffe, N. Kupperman, B. Kaufman, B. Lee, T. Park, W. McAlister, Diagnostic testing of acute head injury in children: When are head computed tomography and skull radiographs indicated? Pediatrics 99 (5) (1997).
[17] A.K. Ommaya, F. Faas, P. Yarnell, Whiplash injury brain damage, JAMA 204 (1968) 285–289.
[18] A.K. Ommaya, P. Yarnell, Subdural hematoma after whiplash injury, Lancet (1969) 237.
[19] T.A. Gennarelli, L.E. Thibault, Biomechanics of acute subdural hematoma, J. Traum. 22 (1982) 680–686.
[20] D. Nuckley, M. Eck, S. Hersted, R. Mizra, R. Ching, Tensile mechanics of the developing baboon cervical spine, in: F.A. Bandak (Ed.), Injury Science Research Proceedings of the 28th International Workshop on Human Subject Biomechanics, Atlanta, Georgia, 2000, pp. 85–89.
[21] R. Ching, J. Nuckley, S. Hersted, M. Eck, F. Mann, Tensile mechanics of the developing cervical spine, Stapp. Car Crash. J. 45 (2001) 329–336.
[22] R. Mayer, F. Pintar, N. Yoganadan, Pediatric neck tensile strength characteristics using a caprine model, in: F.A. Bandak (Ed.), Injury Biomechanics Research, Proceedings of the 27th International Workshop on Human Subject Biomechanics, San Diego, California, 1999, pp. 87–92.

Glossary

Injury Biomechanics: Biomechanics is the subset of the scientific discipline of Mechanics that deals with the forces, motions, deformations, ruptures, fractures, breaks, etc. of living tissue. The science of Biomechanics applies at the microscopic (cellular, sub-cellular, etc.) and the macroscopic (tissue, organ, full body, etc.) scales. Injury Biomechanics is the application of Biomechanics to the understanding of the causation and mechanism of injury.

Normal: in this case ''normal'' means in a direction perpendicular to the arc.

G: is the designated symbol for one unit of gravitational acceleration. On earth, the value of G is 32.2 ft/s^2

N: refers to a Newton, the unit of force or weight.

Rad: is the symbol for radian, which, like degrees, is a measure of angle. Approximately 6 radians represents one revolution or 360 degrees. The actual value for one revolution is 2π radians where π has an approximate value of 3.14.

E_{SF}: infant skull fracture energy.