

The “Shaken Baby” Syndrome; Computational Studies of a New Hypothesis of its Cause

Authors:

J.Cheng, S. Cirovic, I.C. Howard and A. Yoxall, Department of Mechanical Engineering, the University of Sheffield
M.A. Parsons, Department of Ophthalmology and Orthoptics, the University of Sheffield

Correspondence:

Professor I.C. Howard, Department of Mechanical Engineering, the University of Sheffield, Mappin Street, Sheffield S1 3JD, UK
0114 222 7740
0114 222 7890
i.howard@sheffield.ac.uk

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ABSTRACT

The term “shaken baby syndrome” refers to a unique pattern of non-accidental traumatic injury occurring in children by shaking. Typical injuries include subdural haemorrhage, retinal haemorrhage as well as tears to cortical bridging veins. Infants younger than 6 months are significantly more vulnerable to the shaken baby syndrome than older infants and children, a fact that has been difficult to reconcile with all previous explanations of the phenomenon. The paper explores a new hypothesis for the unique vulnerability of infants (i.e. those younger than about 6 months) to shaking: - the different motions of the brain in skulls with and without the flexibility provided by the fontanelles. The investigation involved the study of two highly simplified finite element models of a skull and brain subjected to shaking, namely, one with a representation of the fontanelle, and one without. The results revealed dangerously enhanced local accelerations and shear strains in the region of the fontanelle. These findings provide a potential mechanism for the special vulnerability of infants to shaking, and suggest some reasons why shaking motions can be much more dangerous than those associated with impact.

INTRODUCTION

The Shaken Baby Syndrome (SBS) is a form of child abuse that is traditionally believed to be caused by violent shaking. The consequences of SBS are harsh; up to 200 babies in the UK die each year from the injuries related to the SBS, whereas around twice that number survive with permanent brain damage or visual impairment. Typical injuries include subdural haemorrhage, sub-arachnoid haemorrhage, retinal haemorrhage, the tearing of cortical bridging veins, and minimal or no evidence of external trauma[1, 2]. Forensic experts are frequently called upon to perform post mortem examinations of babies suspected of being SBS victims. The considerable difficulties of diagnosis are compounded by the fact that acknowledgements of abuse are rare; forensic experts are therefore often called upon to try to interpret findings for which there is inadequate explanation, and consequently the correlation between mechanisms of injury and clinical findings can be extremely difficult to make. Furthermore the diagnosis of SBS has far-reaching, and costly, social and legal implications – and though the interests of the child (and its siblings) are paramount one can never ignore the impact that false accusations have upon the family. For a diagnosis in which there are such severe consequences for the victim and for the victim’s family there is still a lack of fundamental understanding on how the injuries are generated. In biomechanical terms, there are two central questions: -

- how a repetitive acceleration of moderate intensity (shaking) causes severe injury, when a single high acceleration traumatic event (impact) usually does not?
- why are the rates of morbidity and mortality in infants younger than 6 months so much higher than those for older children?

The mechanisms of shaking injury are still largely unknown or controversial. A series of mechanical experiments by Duhaime and her colleagues suggested that pure shaking could not cause fatal brain injury in infants because of measured accelerations were below certain head injury criteria[3, 4].

Modelling with Solid Elements

However, these findings have been challenged recently[5, 6] with doubts on the accuracy of the experiments and the lack of constitutive laws to scale head injury criteria from data gathered on adults, primates, or from traffic accidents. Also, recent FE modelling[2] points to a brain having paediatric structure and material properties sustaining more severe damage than in models with properties appropriate to older humans.

A major feature of infant skulls that is not present in those of older children or adults is the softness and flexibility due to the fontanelles and sutures; see Figure 1. This will permit very different motions of the brain in infants with fontanelles in comparison with older children where these have healed significantly. The finite element (FE) modelling described below shows that such softness and flexibility can indeed produce the sort of internal brain motions that are compatible with SBS observations.

Figure 2 shows the idealised FE model of the head of a one-month old infant used in the study. The geometry was simplified from a real infant head (Figure 1) with virtually all geometric detail being neglected. The brain and the cerebrospinal fluid (CSF) were represented by 8-noded solid elements, a the brain mass of 0.5kg, and with the CSF occupying 20% of the brain case[7, 8]. The anterior fontanelle and the scalp were modelled as one layer 1mm thick, with an area of 677.4mm²[9, 10], the rest of the head being enclosed by the skull, 3mm thick. The skull and the fontanelle/scalp were modelled by 4-noded shell elements. All materials were elastic except the CSF, which was modelled as elastic-fluid. The material properties come from the literature[2, 10, 11]. Specifically, the brain had a modulus of 2.5kPa, the skull 1300MPa, and the fontanelle/scalp, 1MPa.

The models studied used the same FE geometry (Figure 2). The “soft skull” model had fontanelle/scalp properties in the region indicated in Figure 2, whilst the “stiff skull” model ascribed infant skull properties to that region.

The input motion trajectory (Figure 3) was selected from the reconstructed curve of one of a series of shaking experiments on an instrumented automotive dummy child[13]. It is consistent with the literature[4]. This motion was applied to the rigid segment of the skull in the gaze direction; the velocity was selected instead of displacement in order to increase the accuracy of the acceleration and displacement obtained by differentiating and integrating from the velocity.

One and half shakes with two reversals of motion were simulated using LS-DYNA[14].

Results

Figure 4 clearly shows the wave-like pattern of deformation that develops at the first reversal of motion near the fontanelle in the soft skull model (A). The stiff skull model (B) has a much more benign pattern.

Since the heavy brain is still moving forward in both models as the skull reverses its motion, its deceleration is accompanied by internal forces that tend to move it upwards and downwards, and the CSF experiences very large shears. At that time, the average acceleration in the gaze direction of the soft skull model is 15 – 20g ($g=9.81\text{ms}^{-2}$), between 1.5 and 2 times that in the stiff skull model. It is the vertical direction where the most significant differences can be seen. The stiff skull model suffers an acceleration of about 1g, whilst that in the soft skull model is 10 to 15 times larger.

Figure 5 displays the distributions of maximum shear stress in both models shortly after the first reversal of motion, and Figure 6 gives more detailed information for the sensitive region of the brain just under the site of the fontanelle. The peak value (1.8kPa) of maximum shear stress is about 6 times larger in the soft skull model than the typical shear stress (0.3kPa) in the stiff skull model. Furthermore, the trace of the signal in the former has a saw-tooth shape with violent and rapid changes at a frequency of 90Hz in short times, while the latter, though increasing with time, is much smoother.

Preliminary FSI Modelling

Figure 7 shows a new preliminary model with fluid structure interaction (FSI). It was developed from the previous solid element model, by combining the brain and CSF into a single fluid mass. The skull and fontanelle/scalp remained the same. The model included suitable void outside the skull into which the fluid could move during the motion. Skulls with and without ventricles were analysed. The prescribed input motion followed the same path as that for the solid element model.

Figure 8 clearly demonstrates the very different motions at the top of the skull in two models. Figure 9 is a time trace of the maximum principal stress in the fontanelle. The value increases rapidly during the third imposed cycle of acceleration and deceleration.

An improved model with the brain suspended inside a CSF layer is under construction.

Discussion

These results suggest that the very different behaviour of the soft-skull model compared with the stiff-skull counterpart might be a **system property** of structures where a large flexible mass is suspended in a liquid, all contained within a stiff outer casing with a top part that was much more deformable than the rest. We explored this by making some very simple tests involving filled balloons suspended in water inside a cup. The cup was sealed by a flexible membrane over the top. When shaken by holding only on the sides of the cup, there was a very obvious “banging” response of the system. This disappeared when the top of the cup was held tight by the other hand.

Realistic results from computational modelling using solid elements of the sort described here depend upon very careful choices for the material properties of the CSF. This is primarily because solid material models do not easily exhibit the fluid-like shear that is needed to accommodate realistic brain deformations inside the skull. The way forward is to develop suitable fluid/solid models with the CSF being represented by the fluid phase. Work towards this goal has begun, and the preliminary results from a skull-type shell containing CSF-type liquid is very enlightening. An opening that models the fontanelle allows completely different CSF motions to the top of the model compared with a similar one with a closed top. There also appears to be a build-up of deformation, a feature that could contribute to a ratchetting effect.

If these suspicions prove sound, modelling of the sort shown here should prove to be a very important tool for investigating the fundamental mechanics of the important SBS phenomena.

Conclusions

- A new hypothesis for the special vulnerability of infants to shaking has been proposed and studied.
- The softness due to the fontanelle and suture lines in the skulls of infants creates very different and dangerous patterns of local acceleration and shear in skulls with fontanelle-type soft areas compared with those without.
- The qualitative behaviour of the computational modelling is consistent with engineering expectation.
- Fluid-structure interaction is essential in any sound model of biomechanical phenomena such as those described here
- Any conclusions drawn from these results must be treated as temporary and tentative until, at least, some experimental validation becomes available.

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