Finite Element Modelling of Impact-induced Axonal Injury in Sheep

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Summary

This paper describes a numerical study of axonal injury caused by an impact to the head of the anaesthetised sheep. In the model, described in Anderson et al. (2003), injury is closely related to the peak impact force and to kinematic measurements, particularly the peak change in linear and angular velocity. A three-dimensional finite element model of the sheep skull and brain was constructed to simulate the dynamics of the brain and skull during the impact. Model validation was attempted by comparing pressure measurements in the experiment with those calculated by the model. The distribution of axonal injury was then compared with the output of the finite element model. The finite element model could account for approximately thirty per cent of the variation in the distribution and extent of axonal injury.

Introduction

Our research group recently reported the characteristics of a sheep model of axonal injury (Anderson et al., 2003). This model has the characteristic that axonal injury throughout the brain is related to the dynamics of the impact. The model uses comprehensive mechanical measurements to characterise the impact, including impact force, linear and angular kinematics and intracranial pressure rise due to impact phenomena. Axonal injury is mapped at high resolution throughout the brain volume. These measurements allow numerical techniques, such as the finite element method, to be used to simulate the dynamics of the brain during the impact and to relate the results of the simulation to the distribution of axonal injury. The ability to numerically model the incidence of axonal injury would be valuable for determining tolerable levels of impact in engineering applications, such as designing head protection for automotive crashes. This paper reports on the results of a finite element simulation of the sheep model of axonal injury reported in Anderson et al. (2003).

Materials and Methods

A finite element (FE) model was constructed to simulate the experiments reported in Anderson et al. (2003). A sheep from the same flock as the experimental animals was used to record the geometry of the brain and skull using serial MRI and CT scans. Image analysis software was used to detect the boundaries between structures within the head of the animal in the image data, and these were used to create a finite element mesh, for solving within the software LS-DYNA. The tentorium was not easily defined from the image data, and so the geometry of this structure was measured using the three-dimensional digitiser. The mesh is illustrated in Figure 1. Details of the mesh are given in Table 1.

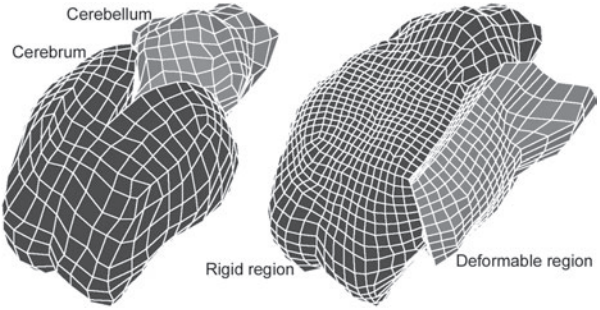

Figure 1 Finite element mesh of the cerebrum and cerebellum (left) and the skull (right). The model of the tentorium is not shown.

Table 1 Element numbers for the mesh of the sheep skull and brain (see Hallquist, 1988 for details of element formulations)

Component	4 node shell elements*	Constant stress solid elements	Fully integrated S/R solid elements	Total
left hemisphere		112	912	1024
right hemisphere		113	911	1024
cerebellum		216	648	864
tentorium	428			428
contact region of skull		1024		1024
rigid part of skull	1271			1271
Total				5635

*Hughes- Liu formulation unless defined as rigid

The impact to the head was simulated by constraining the skull to follow the kinematics of the impact as recorded in the experiment, while the impact force was applied to a deformable region of the head to simulate the bending of the skull in this region. The impact point was measured with a three dimensional digitiser. The recorded impact force was applied to the corresponding region on contact region of the model.

Viscoelastic properties were assigned to the brain, and the brain/skull interaction used a ‘sliding but no separation’ contact algorithm (to mimic the CSF layer). The foramen magnum was represented with a stress free boundary.

Pressure measurements were made at two locations on the surface of the brain in most experiments. The transducers were placed in the skull so that the sensor read the pressure changes at the surface of the brain. These measurements were used to check the validity of the response of the finite element model to a simulated impact. One sensor was located near the point of impact, and another near the far side of the cranial cavity. The positions of the transducers were measured using a digital 3-D digitiser. The results of the finite element simulation were then processed to extract the pressure histories at the locations of the pressure transducers, and these histories could be compared to the pressures measured in the experiment as a validation of the model’s behaviour. The comparison of pressure responses in three experiments is shown in Figure 2. The magnitude of the pressure response of the FE model is similar to the experiments, while there are some clear differences in the phase of the response.

The FE model was then applied to simulate the kinematics of nine

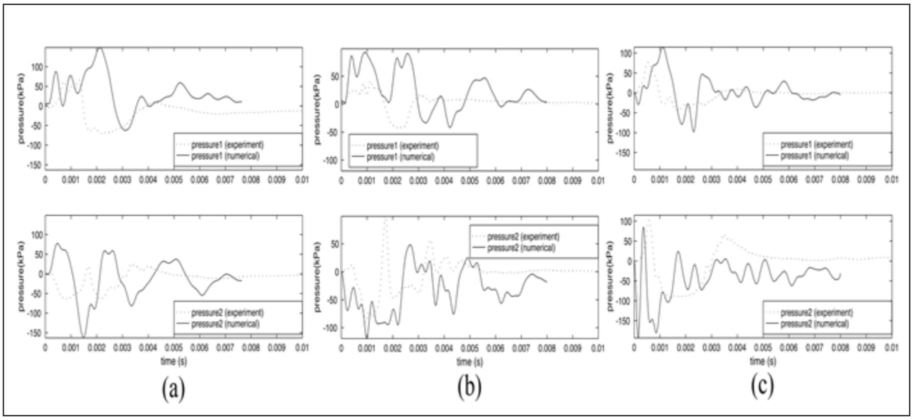

Figure 2 Pressures predicted by Model B, and those recorded in Experiment 0398 (a), Experiment 0498 (b) and Experiment 0598 (c). Pressure 1 is the pressure measured on the near side and pressure 2 is that measured on the side further from the impact point.

head impact experiments. The results of the simulation were then analysed to allow a comparison with the injury in the actual experiment.

The identification of the injury in the sheep was made using immunohistological methods and is described in detail in Anderson et al. (2003). A grid survey of the incidence of injury was conducted on three evenly spaced coronal sections of the cerebrum. Each section was split into quarters (sectors) about the grid centre. The percentage of grid squares in each sector containing axonal injury was calculated. This percentage was the sector axonal injury score (SAIS). Each animal therefore produced 12 surveyed sectors, each sector with a corresponding SAIS.

To facilitate the comparison between model predictions and injury (defined by the SAIS), results had to be extracted from the model on the equivalent coronal plane of each slice. This was done by visually identifying the position of the histology section in the MRI data that were used to build the FE model. This plane could then be described numerically, so that the FE model could be sectioned at the equivalent location.

Table 2 Material properties used in the finite element model

	Density	Young's Modulus	Poisson's ratio	Short and long term shear modulus and decay constant	Bulk modulus	Ref.
Skull	3000 kg/ m^3	6.5×10^9 Pa	0.22			(1)
Brain	1040 kg/ m^3			$G_0 = 4.9e4$ Pa $G_\infty = 1.67e4$ Pa $\beta = 145\ s^{-1}$	1.25e6 Pa	(2)
Tentorium	1130 kg/ m^3	3.15×10^7 Pa	0.45			(3)

(1) Claessens et al. (1997), (2) Kang et al. (1997), (3) Ruan et al. (1997)

Results

Initial simulations were of experiments that had high quality kinematic measurements (see Anderson et al., 2003) and fracture was absent or of a minor nature. The analysis of these experiments was then compared to the results of simulations from all experiments.

The Sector Axonal Injury Score (SAIS) was compared with the maximum value of the stress parameter, the von Mises stress, arising within the sector over the simulation. This was designed to characterise the most severe mechanical stress occurring within the sector during the impact. One sector's SAIS was excluded in ithe initial analysis due to the presence of artefact in the histology of that sector.

A plot of the SAIS and the corresponding peak von Mises stress calculated in the finite element model is shown in Figure 3. The initial simulation produced a correlation between von Mises stress and the SAIS that was highly statistically significant ($p = 0.0007$). However, the correlation is such that, the calculated von Mises stress in the model accounted

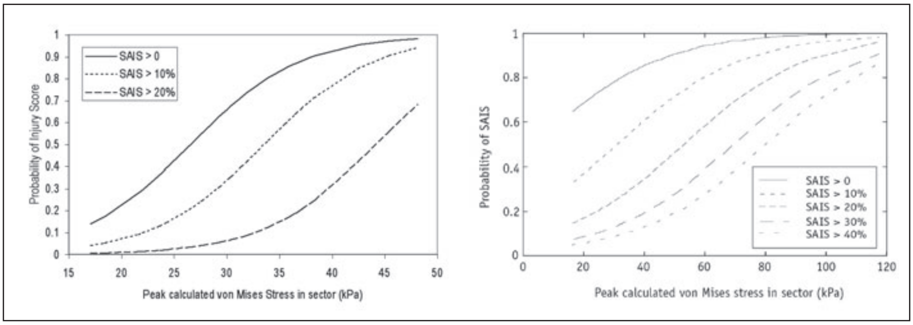

Figure 3 Relationship between peak von Mises stress in Model B and the Sector Axonal Injury Score of each sector. Left, *Three experiments with no significant fracture, one sector excluded due to artefact (n = 35, R = 0.544, p = 0.0007).* Right, *All experiments and sectors (n = 108, R = 0.391, P = 0.00003).*

for 29.6% of the variation in the SAIS ($R^2 = 0.296$). The correlation between the von Mises stress and the SAIS was even lower when the analysis was extended to all simulations. This was expected as fracture would alter the pattern of stress during the impact, and the presence of contusions might have affected the SAIS. Notwithstanding these effects, the peak von Mises stress in the model was still able to account for approximately 21 per cent of the variation in the SAIS.

The simulation results were further interrogated to build a probabilistic model of axonal injury. This model describes the probability of the incidence of a certain SAIS in a sector of the brain of the sheep, in these experiments, using the von Mises stress as a predictor. The probabilistic model was constructed by stratifying the Sector Axonal Injury Scores (SAIS) into categories and performing an ordinal logistic regression on the data. The method of regression is based on that described in McCullagh (1980). The resulting cumulative probabilities are shown in Figure 4.

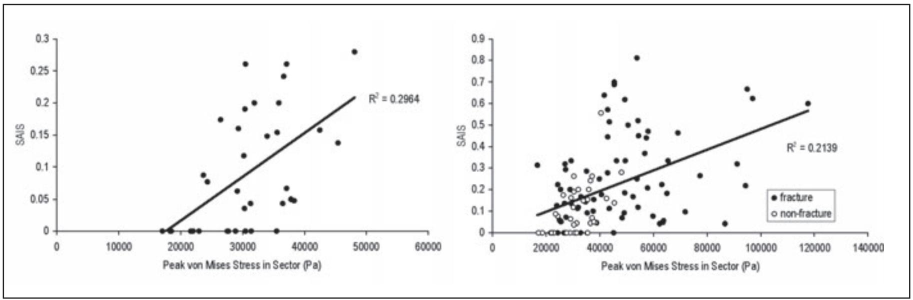

*Figure 4 Ordinal logistical regression comparing predicted von Mises stress in the model and the extent of axonal injury in three experiments with no significant skull fracture (*left*) and all experiments (*right*).*

Conclusions

The results from the simulation of experiments where fracture did not complicate the pathology in any way produced the highest correlation between the model and axonal injury ($R^2 = 0.296$). Clearly most of the variation in SAIS is still unaccounted for. Simplifications inherent in the injury scoring method and in the chosen measure of stress introduce errors, which may account for some of the variation in the results. Also, inaccuracies in the model would contribute; there are several numerical aspects of the model that need to be verified and model validation should be improved. It is also possible that the mechanism of injury is not sufficiently represented by von Mises stress and a better correlate could exist. Despite the manifold potential sources of inaccuracy, the model could predict a sizeable proportion of the variability in the SAIS, with a high level of statistical significance.

When we compare the graphs in Figure 4, the curves produced from all experiments are further toward the top left corner of the axes than the curves produced in the initial analysis. This means that, when the results from all experiments are used, higher sector axonal injury scores are predicted for the same estimate of von Mises stress. This suggests that fracture affected the SAIS directly in these experiments, and the higher injury scores were not just a result of higher inertial loads. This could have been caused by altered patterns of stress in the brain, and/or through increased levels of contusion. It is probable that the FE model underestimated the stress produced in experiments where there was a fracture. The model does not reproduce the effects of bone displacement, which might have produced concentrated loads, and larger distortions to the cranial volume. Note that the probabilistic models for the SAIS in this paper describe the relationship between injury observed in the experiments and the mechanics predicted by the FE model used. Although it would be tempting to generalise the curves in Figure 4, more model development is required, and better validation needed, before it would be possible to do so.

References

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