Improvements for Simulating Cerebral Edema and Delayed Fatality after Traumatic Brain Injury using Triphasic Swelling Biomechanics

Andrew V. Basilio, Leanne Pichay, Peng Xu, Yukou Takahashi, Toshiyuki Yanaoka, Hisaki Sugaya, Gerard A. Ateshian, Barclay Morrison III

I. INTRODUCTION

Traumatic brain injury (TBI) is a major contributor to mortality and morbidity after motor vehicle crashes (MVCs). In 2013, 21.5% of TBI-related hospitalisations in the United States were attributed to MVCs [1]. In an effort to reduce the societal costs of MVCs, finite element (FE) models have increased our understanding of injury causation, as well as aided in the design of improved safety systems for both occupants and vulnerable road users. Current FE models in the automotive industry focus on predicting stress and strain during the accident in order to predict primary injury, but contemporary models have not been used to simulate delayed brain swelling from edema due to mechanical inputs following a MVC, which occurs after the impact on a time-scale of hours to days. Over 70% of severe TBI patients (GCS ≤ 8) experience cerebral edema leading to increased intracranial pressure (ICP), and elevated ICP is highly associated with poor outcome and increased mortality [2]. Herein, we continue the development of a computational strategy [3-4] that may help to predict the pattern and magnitude of cerebral edema that occur subsequent to primary injury. By simulating cerebral edema, it may be possible to improve prediction of mortality during this sub-acute phase to inform the design of novel safety systems. Ultimately, our model is still in the process of being validated. In this current study we have refined the relationships governing primary cell death, ischemic cell death and mortality due to ICP.

II. METHODS

The solid matrix within cells is composed of material with inherent negative charge (proteins, glycosaminoglycans, DNA, etc.), represented by the concept of a fixed charge density (FCD). Under resting conditions, we hypothesise that the FCD is under-hydrated because of the charge imbalance induced by the sodium-potassium pumps, which has major implications for brain swelling after injury, and that the degree of FCD exposure (in a continuum sense) is related to cell death. Tissue swells as FCD becomes exposed due to cell death because of the Gibbs-Donnan effect [5]. We hypothesise that cell death is dependent on the maximum principal strain (MPS) experienced by brain tissue during impact, as is often assumed in FE modelling, as well as ischemia due to compression of brain tissue. In our previous paper, we modelled post-TBI edema using FEBio (febio.org) [6-7], which includes triphasic material formulations and thus allowed us to model swelling due to the Gibbs-Donnan effect to calculate the resulting ICP and associated fatality probability for a particular crash scenario [3]. More details of our methodology are presented in Basilio *et al* [3] .

Since our previous publication [3] in which swelling was modelled based on an initial mechanical insult and again following ischemia due to compressed brain tissue, we have modified both the MPS-to-cell death and ischemia-to-cell death relationships after reviewing more literature [8]. The amount of damage (D) that an element experienced, whether due to MPS or compression-induced ischemia, was assumed to obey a log-normal cumulative distribution function:

$$D = \frac{1}{2}\operatorname{erfc}\left[-\frac{ln\left(\frac{x}{\mu}\right)}{\sigma\sqrt{2}}\right] \qquad \text{(Eq. 1)}$$

where x represents the MPS of an element in the MPS-to-cell death relationship, x represents 1-J (J being the volume ratio of an element) in the ischemia-to-cell death relationship (i.e. compression), μ and σ represent the midpoint and spread of the cumulative distribution function, respectively. μ and σ for the updated best-fit functions were calculated using MATLAB (Fig. 1).

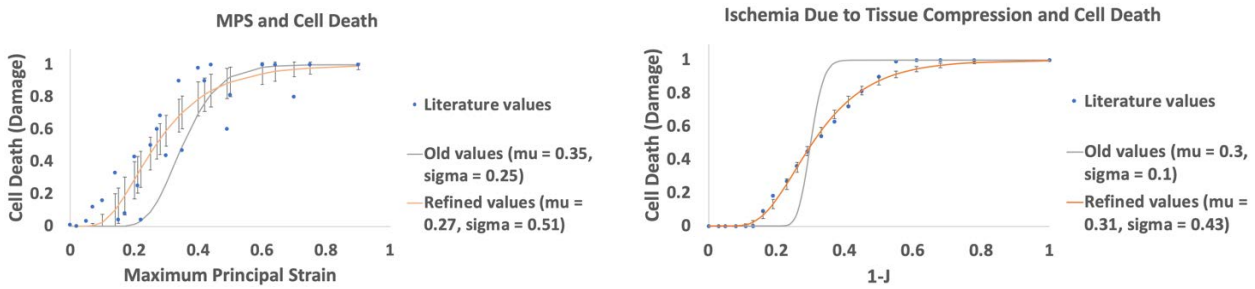

Fig. 1. Left figure shows a scatter plot of cell death vs. MPS generated from an extensive review of the available literature, our previous fit to the data, and our current modified fit. Right figure shows a scatter plot of cell death vs. 1-J from the literature, our previous fit to the data, and our current modified fit.

Andrew Basilio (avb2132@columbia.edu) is a PhD candidate in biomedical engineering at Columbia University. Leanne Pichay (lap2203@columbia.edu) is an undergraduate student in biomedical engineering at Columbia University. Peng Xu (pengxu@buaa.edu.cn) is a PhD candidate in the School of Biological Science and Medical Engineering at Beihang University. Yukou Takahashi (yukou_takahashi@n.t.rd.honda.co.jp), Toshiyuki Yanaoka (toshiyuki_yanaoka@n.t.rd.honda.co.jp), and Hisaki Sugaya (hisaki_sugaya@n.t.rd.honda.co.jp) are engineers at Honda R&D Co., Ltd. Gerard A. Ateshian (ateshian@columbia.edu) is the Andrew Walz professor of mechanical engineering and professor of biomedical engineering at Columbia University. Barclay Morrison III (bm2119@columbia.edu) is a professor of biomedical engineering at Columbia University.

III. INITIAL FINDINGS

After simulating swelling due to strain and ischemia using the new μ and σ values, ICP (the volume averaged 3rd principal stress of all multiphasic elements in the mesh) stabilised after the second round of ischemic swelling for all severe and fatal vehicle-to-pedestrian impact cases tested (Fig. 2). Cases are from the Pedestrian Crash Data Study (PCDS) and Crash Injury Research (CIREN) data bases. Detailed methodology regarding simulation of initial swelling and ischemic swelling can be found in our previous paper [3].

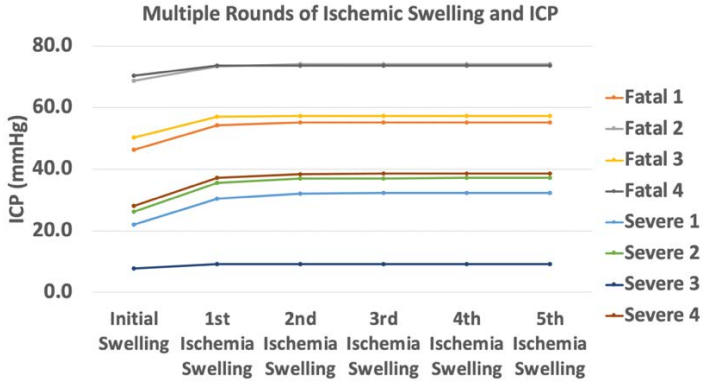

Fig. 2. ICP over multiple rounds of ischemic swelling. For each case, ICP stabilised after the second round of ischemia.

We also modelled pressure due to the space-occupying effect of blood on the brain due to ruptured bridging veins (Fig. 3) and have seen increases in ICP when modelling large subdural haemorrhages.

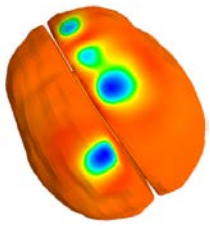

Fig. 3. Blue spots represent arbitrarily sized areas of applied pressure corresponding to locations where BVs have exceeded ultimate strain during a vehicle-to-pedestrian impact scenario.

IV. DISCUSSION

Prior to using the new μ and σ values, ICP continued to increase after each subsequent round of ischemic swelling for all tested cases, with some severe and some fatal cases approaching 100% fatality probability. If left unaddressed, this issue would cause difficulties in differentiating ICP and associated fatality probability between severe and fatal cases. Incorporating the refined μ and σ values allowed ICP to plateau for all eight cases tested, showing that ICPs from fatal cases are consistently higher than ICPs from severe cases, at least for these tested cases. However, some limitations need to be addressed. One issue is that the FCD of the brain needs to be experimentally validated. As FCD dictates the physics of swelling, we need to determine the FCD of brain tissue to validate our model. We also need to do more research to determine what factors influence the size and shape of haematomas. It is possible that the increased fatality rate from the presence of haematomas is attributable to more than just the space-occupying effect of the blood; we may need to consider inflammation and other mechanisms. In the near future, we also hope to use our model to predict outcomes following severe injury, such as coma, cognitive defects and other neurological deficits, by observing damage to particular areas of the brain and white matter tracts in addition to predicting mortality. We hope this work will one day assist automotive safety engineers' efforts to save more lives and preserve the quality of life for victims of MVCs.

V. REFERENCES

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