

High-fidelity finite element modelling of brain angioarchitecture for a rat model of traumatic brain injury

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I. INTRODUCTION

Traumatic brain injury (TBI) is the leading cause of death and disability in young adults [1]. TBI is caused by mechanical forces that damage neurons, axons and vessels. Vascular damage is a key injury in the acute phase of TBI and a recent study has shown an association between vascular injury and patient outcome after TBI [2]. However, it is still not understood how mechanical forces translate to vascular changes and aggravate secondary injury cascades. Here we incorporated detailed anatomy of vasculature in a high-fidelity Finite Element (FE) model of TBI in rats [3] to predict the distribution of mechanical forces across the vascular network and determine its association with the vessel's anatomy.

II. METHODS

We have developed a high-fidelity FE model of a rat brain tissue and its angioarchitecture based on high-resolution images of the brain to simulate Controlled Cortical Impact (CCI). Our FE model was validated according to the lesion maps acquired from rats subjected to CCI, using the same parameters. We used our validated model to predict the stress wave propagation across the brain vasculature and to investigate the interaction between stress wave within the brain tissue and vessels network.

3D Image of the Brain

A new high-resolution map of the post-mortem rat brain angioarchitecture was employed to create our model, acquired with synchrotron radiation phase contrast imaging (SR-PCI) technique, yielding a final resolution of $5.92 \times 5.92 \times 5.92 \mu\text{m}^3$ [4]. We used Image-Pro [5] to reconstruct the 3D map of the angioarchitecture, which resulted in illustrating the vessels with a minimum diameter of $10 \mu\text{m}$.

Controlled Cortical Impact Tests

General surgery and CCI procedure were carried out based on previous work [6-7]. A ~6 mm unilateral rectangular craniotomy, -0.5mm to -6.5 mm posterior and + 3.5 mm lateral to Bregma, was performed on each animal using a high-speed microdrill with a 0.45 mm drill bit. Injury was induced with a 5 mm flat electromagnetically driven steel impactor, which struck the exposed dura at ~4 m/s and an impact depth of 2 mm. We used the brain lesion map based on 9.4T high-resolution T2 acquired from injured animals two weeks post-injury to validate our FE model prediction.

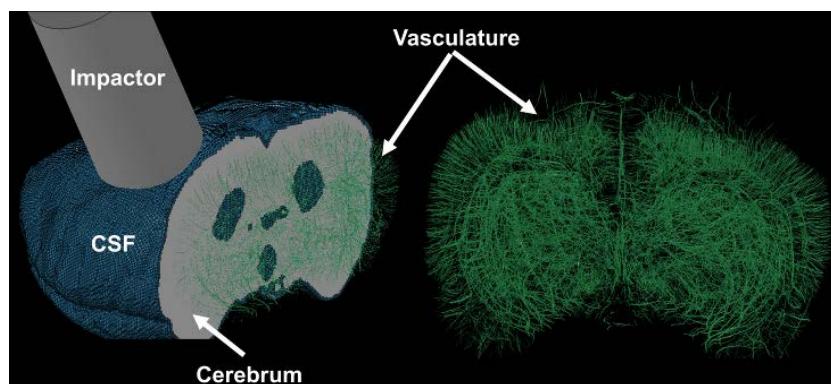


Fig. 1. Finite model of the CCI test (left) and FE model of the angioarchitecture of the brain (right).

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Computational Modelling

An inhouse MATLAB code was used to generate a 3D FE model of the CSF, cerebrum, ventricles and vasculature. We modelled the brain tissue using solid elements and a visco-hyperelastic material model and the vasculature was modelled using beam elements and an elastic material model [8-9]. We used this model to simulate the CCI (Fig. 1) and predict the distribution of mechanical forces in the vessels. We also developed microscale models of regions of interest to predict forces in capillaries.

III. INITIAL FINDINGS

We found good agreement between the volume of the lesion and the volume of the brain exceeding a 35% strain threshold [3]. Both lesion and strain maps showed larger injury near the edges of the impactor. We predicted large axial stresses in the ipsilateral cortical vessels, with maximal stresses being concentrated in vessels that are close to the edges of the impactor (Fig. 2, left). Interestingly, the cortical vessels directly under the impactor, which are mainly aligned with the direction of penetration, were not subjected to large forces. However, in the corpus callosum below the impacted cortex, where vessels are mainly running perpendicular to the direction of penetration, our model predicted large axial forces in the vessels. Using the microscale modelling, we predicted axial stresses in a small region containing a few capillaries (Fig. 2, middle and right). Our results show that axial forces vary significantly across individual capillaries that are few microns apart.

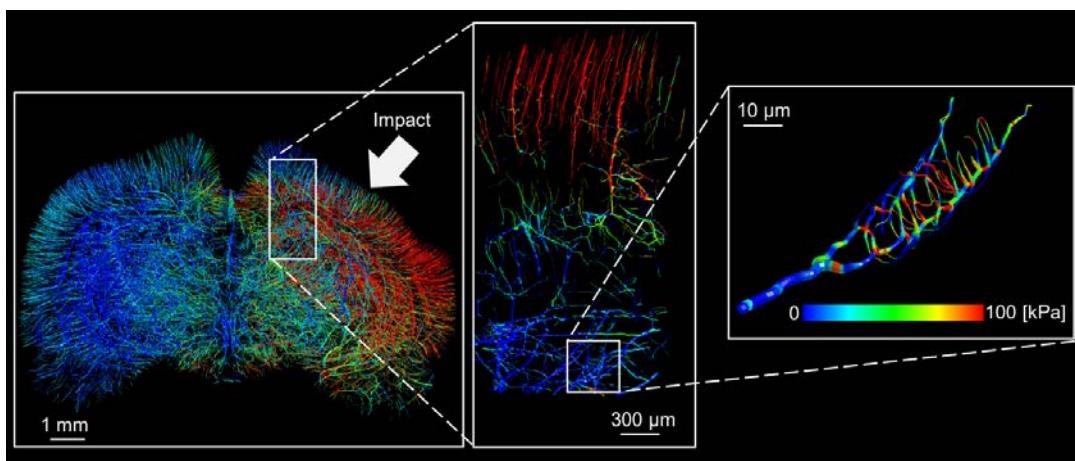


Fig. 2. Axial stress of the brain vasculature at different scales: the whole angioarchitecture (left), region of interest (middle), capillaries (right).

IV. DISCUSSION

We have developed the first FE model of vascular injury in rats, which incorporates high fidelity anatomy of vasculature down to micrometre resolution. This allowed us to predict mechanical forces in vessels immediately after CCI and to determine the interaction between the brain tissue, the anatomy of neurovasculature and stress distribution across scales. Our work shows that the vascular network can influence the stress distribution in the individual vessels and capillaries. In future work, we will compare our computational predictions with high-field MR images and histopathology to better understand the effects of mechanical forces in producing vascular pathology.

V. REFERENCES

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