Finite Element and Neuroimaging Techniques to Improve Decision-Making in Clinical Neuroscience

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Abstract

Our brain, perhaps the most sophisticated and mysterious part of the human body, to some extent, determines who we are. However, it’s a vulnerable organ. When subjected to an impact, such as a traffic accident or sport, it may lead to traumatic brain injury (TBI) which can have devastating effects for those who suffer the injury. Despite lots of efforts have been put into primary injury prevention, the number of TBIs is still on an unacceptable high level in a global perspective.

Brain edema is a major neurological complication of moderate and severe TBI, which consists of an abnormal accumulation of fluid within the brain parenchyma. Clinically, local and minor edema may be treated conservatively only by observation, where the treatment of choice usually follows evidence-based practice. In the first study, the gravitational force is suggested to have a significant impact on the pressure of the edema zone in the brain tissue. Thus, the objective of the study was to investigate the significance of head position on edema at the posterior part of the brain using a Finite Element (FE) model. The model revealed that water content (WC) increment at the edema zone remained nearly identical for both supine and prone positions. However, the interstitial fluid pressure (IFP) inside the edema zone decreased around 15% by having the head in a prone position compared with a supine position. The decrease of IFP inside the edema zone by changing patient position from supine to prone has the potential to alleviate the damage to axonal fibers of the central nervous system. These observations suggest that considering the patient’s head position during intensive care and at rehabilitation should be of importance to the treatment of edematous regions in TBI patients.

In TBI patients with diffuse brain edema, for most severe cases with refractory intracranial hypertension, decompressive craniotomy (DC) is performed as an ultimate therapy. However, a complete consensus on its effectiveness has not been achieved due to the high levels of severe disability and persistent vegetative state found in the patients treated with DC. DC allows expansion of the swollen brain outside the skull, thereby having the potential in reducing the Intracranial Pressure (ICP). However, the treatment causes stretching of the axons and may contribute to the unfavorable outcome of the patients. The second study aimed at quantifying the stretching and WC in the brain tissue due to the neurosurgical intervention to provide more insight into the effects upon such a treatment. A nonlinear registration method was used to quantify the strain. Our analysis showed a substantial increase of the strain level in the brain tissue close to the treated side of DC compared to before the treatment. Also, the WC was related to specific gravity (SG), which in turn was related to the Hounsfield unit (HU) value in the Computerized Tomography (CT) images by a photoelectric correction according to the chemical composition of the brain tissue. The overall WC of brain tissue
presented a significant increase after the treatment compared to the condition seen before the treatment. It is suggested that a quantitative model, which characterizes the stretching and WC of the brain tissue both before as well as after DC, may clarify some of the potential problems with such a treatment.

Diffusion Weighted (DW) Imaging technology provides a noninvasive way to extract axonal fiber tracts in the brain. The aim of the third study, as an extension to the second study was to assess and quantify the axonal deformation (i.e. stretching and shearing) at both the pre- and post-craniotomy periods in order to provide more insight into the mechanical effects on the axonal fibers due to DC.

Subarachnoid injection of artificial cerebrospinal fluid (CSF) into the CSF system is widely used in neurological practice to gain information on CSF dynamics. Mathematical models are important for a better understanding of the underlying mechanisms. Despite the critical importance of the parameters for accurate modeling, there is a substantial variation in the poroelastic constants used in the literature due to the difficulties in determining material properties of brain tissue. In the fourth study, we developed a Finite Element (FE) model including the whole brain-CSF-skull system to study the CSF dynamics during constant-rate infusion. We investigated the capacity of the current model to predict the steady state of the mean ICP. For transient analysis, rather than accurately fit the infusion curve to the experimental data, we placed more emphasis on studying the influences of each of the poroelastic parameters due to the aforementioned inconsistency in the poroelastic constants for brain tissue. It was found that the value of the specific storage term \( S_{\text{epsilon}} \) is the dominant factor that influences the infusion curve, and the drained Young’s modulus \( E \) was identified as the dominant parameter second to \( S_{\text{epsilon}} \). Based on the simulated infusion curves from the FE model, Artificial Neural Network (ANN) was used to find an optimized parameter set that best fit the experimental curve. The infusion curves from both the FE simulations and using ANN confirmed the limitation of linear poroelasticity in modeling the transient constant-rate infusion.

To summarize, the work done in this thesis is to introduce FE Modeling and imaging technologies including CT, DW imaging, and image registration method as a complementary technique for clinical diagnosis and treatment of TBI patients. Hopefully, the result may to some extent improve the understanding of these clinical problems and improve their medical treatments.

**Key Words**

Traumatic brain injury, Intracranial Pressure, Brain edema, Gravitational force, Finite Element Model, Poroelastic parameter, Decompressive craniotomy, Image registration, Water content, Strain level, Diffusion Weighted Imaging