Effects of Brain Tissue Mechanical and Fluid Transport Properties during Ischaemic Brain Oedema: A Poroelastic Finite Element Analysis

Mohd Jamil Mohamed Mokhtarudin
Faculty of Mechanical Engineering
Universiti Malaysia Pahang
Pekan, Pahang, Malaysia
mohdjamil@ump.edu.my

Abbas Shabudin
Faculty of Mechanical Engineering
Universiti Malaysia Pahang
Pekan, Pahang, Malaysia
abbasshabudin@gmail.com

Stephen J. Payne
Institute of Biomedical Engineering,
Department of Engineering Science
University of Oxford
Oxford, United Kingdom
stephen.payne@keble.ox.ac.uk

***Abstract*— Reperfusion after ischaemic stroke is risky as it can result in the formation of brain oedema and brain tissue swelling, which subsequently leads to brain herniation. Brain herniation is an undesirable condition that may affect brain functionality and fatality. A mathematical model based on poroelastic model has been previously developed to describe brain oedema formation. In that model, the brain tissue is assumed as a homogeneous isotropic material. In this paper, the effects of the brain mechanical and fluid transport properties on brain oedema progression are investigated by solving the model in a realistic brain geometry using finite element scheme. Four model parameters, namely brain tissue Young's modulus, Poisson's ratio, water permeability, and viscosity are varied so that their effect on brain oedema formation can be investigated. The results show that the brain Young's modulus and Poisson's ratio play more important role in brain oedema formation compared to the water permeability and viscosity, when varying within certain limits. From these findings, the brain tissue mechanical properties must be optimized so that the model can be used extensively for patient-specific brain oedema progression prediction.**

Keywords—Poroelastic Theory, Brain Oedema, Ischaemia-Reperfusion, Brain Tissue Mechanics, Brain Water Transport.

I. Introduction

Brain herniation occurs when a part of the brain within the skull is being pushed as a result of an increase in the intracranial pressure (ICP). This phenomenon can be observed under the MRI and CT scans by the movement of the midline structures, particularly the brain ventricles. Brain herniation is usually used as an indicator of the occurrence of brain oedema or brain tissue swelling. Brain oedema formation has been observed in ischaemic stroke patients that received reperfusion treatments such as using mechanical catheterisation or by recombinant tissue plasminogen activator (rtpa) administration. Herniation is undesirable because it may lead to the compression of brain microvessels, resulting in secondary ischaemic stroke [1].

Current ischaemic stroke treatments must be given within a short time windows of up to 4.5 hours (if using rtpa), whereby treatments given after this time may increase the risk of ischaemia-reperfusion injury such as brain oedema [2]. However, most patients usually arrived late to the hospital due to many circumstances such as heavy traffic and late detection of stroke occurrence. Therefore, predicting the progression of brain oedema will greatly help neurosurgeon in determining the suitability of an ischaemic stroke treatment to prevent the occurrence of brain herniation, especially for patients that arrived late for the treatments.

A mathematical model describing the formation of brain tissue swelling after ischaemia-reperfusion treatment has been previously developed [3-5] using poroelastic theory. This theory is initially developed to investigate soil consolidation phenomena [6], but has been extensively used to model fluid transport in biological tissue. The brain tissue is assumed to contain water and blood permeable in a porous solid matrix structure. The solid matrix is further assumed as linear elastic, homogeneous, and isotropic. In addition, the water and blood permeability and viscosity are also assumed to be isotropic and homogeneous. These assumptions were made for the sake of simplification of the model, while in fact the mechanical and fluid transport properties in the brain may be different from one patient to another.

In this paper, the mathematical model developed will be solved in a realistic brain geometry using finite element scheme of poroelastic model. Then, the effect of varying the brain tissue Young's modulus, Poisson's ratio, water permeability, and viscosity will be investigated. This results will be used as a preliminary study to determine the importance of these parameters towards predicting brain oedema formation and also for estimating suitable parameters value. Currently, the value of these parameters were taken from related literature. However, each patient should have different parameters value which require estimation and optimization.

II. Methodology

A. Brain Oedema Formation by Capillary Filtration Model

Brain tissue region affected by ischaemia will experience lack of oxygen and nutrient due to blood flow reduction. This will initiate a series of biochemical reactions that destroys the endothelial cells lining the cerebral microvessels, resulting to

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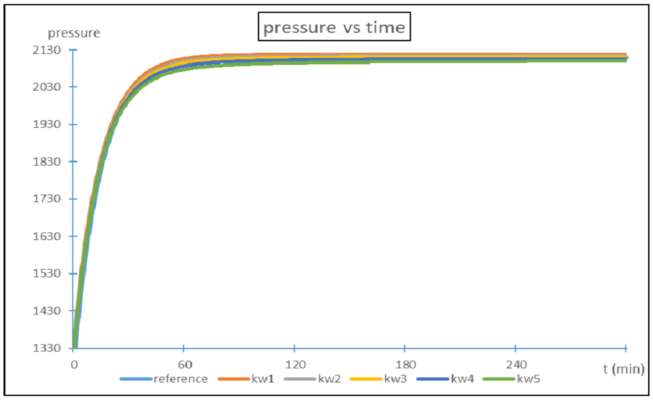

Fig. 10. Brain tissue interstitial pressure for different water viscosity μ_w.

IV. Discussion

In this study, it is found that the brain tissue mechanical properties greatly affect the formation of brain oedema. These properties are the brain tissue Young's modulus and Poisson's ratio. Study done by [7] on the stiffness of brain tissue during transient ischaemic injury using ultrasound elastography found that brain oedema may be determined by the changes in the brain stiffness. Another study by [8] suggested that brain tissue elasticity decreases as a result of the brain structural loss after ischaemia. These findings suggested that brain tissue mechanical properties are important in determining the development of brain oedema.

In this model, brain tissue mechanical properties have been assumed to be linearly elastic. Linear elastic assumption has been used because the brain tissue displacement during brain tissue swelling is assumed to be very small as compared to other pathophysiological cases, for example, traumatic brain injury [9].

On the other hand, when varying the brain tissue water permeability and viscosity, there are no significant changes on the brain tissue displacement and interstitial pressure. Even though these parameters seem to not affect brain oedema formation directly, interstitial water diffusion in the porous brain structure does play an important role in determining the region of brain tissue affected by ischaemia. Water diffusion in the tissue has been extensively used in the assessment of the cell membrane integrity in pathological brain. To effectively assess the water transport properties in the brain, the model requires a modification to include water diffusion equation, as has been done, for example, in [10]. However, it should be noted that water diffusion in the brain tissue depends on the porosity and interstitial space volume, which all depends on the brain tissue mechanical properties [11]. Modification of the model are necessary to include the effect of water diffusion, which will be dealt in the future.

V. Conclusion

The model presented here is used to understand brain oedema formation after ischaemia-reperfusion, which has four important parameters related to the brain mechanical and fluid transport properties. However, only the brain mechanical properties, namely the Young's modulus and Poisson's ratio,

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