

Simulation of Craniectomy Size in Decompressive Craniectomy for Ischaemic Stroke



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Abstract Decompressive Craniectomy (DC) surgery is recommended to treat patients who suffered from large ischaemic cerebral infarction. Although DC surgery has been proven to reduce intracranial pressure (ICP) within the skull, too large of DC opening may contribute to risk of tissue injury. Computational studies nowadays are very useful in predicting and decision making, especially in clinical studies. Therefore, a simulation was performed using mathematical modeling on an idealized 3D brain model to evaluate the outcome of different skull opening sizes in DC towards treating the brain tissue swelling in ischaemic stroke. The model is simulated based on poroelastic theory and capillary filtration. Our results show that larger craniectomy size may reduce the midline shift of the ventricle due to swelling tissue. Nevertheless, the bulging of swollen tissue out from the skull opening causes a little amount of stress applied at the edges of the opening. This modelling work may be used for further research in further research in evaluating the suitable craniectomy size for DC.

Keywords Decompressive craniectomy · Stroke · Poroelastic theory · Craniectomy size

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1 Introduction

Large hemispheric infarction may contribute to the elevation of intracranial pressure (ICP) which can result in brain herniation. The failure of medical treatment to relieve the increasing of ICP in brain has led to the seeking of alternative treatments. Therefore, decompressive craniectomy (DC) surgery may be an effective treatments in treating patients with large brain infarction after ischaemic stroke by creating an additional space to allow for the swelling tissue to extend outward from the skull by removing a portion of bone flap of the skull [1].

In this surgery, the skull opening size is one of the important parameters before the removal process. Large skull opening has always been recommended to reduce the brain swelling. However, too large bone flap removed causes higher risk for complications to occur after the surgery such as infection and hydrocephalus [2]. The minimum diameter of 12 cm for skull opening has been extensively used to minimize ICP level in the brain [3]. The results shown in this article is that 57% of patients who undergo the surgery with skull opening less than 12 cm are found dead after the treatment due to haematoma evacuation and decompression [4].

Computational studies nowadays have been proven to be useful in predicting the clinical outcome and decision making for clinical practice [5]. Hence, in this article, we will evaluate the effect of different sizes of skull opening in minimizing the outcome for swelling of brain tissue due to prolonged ischaemic period by developing the dealized model of 3D brain and application of mathematical modeling based on theory of poroelastic and filtration of capillary previously developed in [6]. Four different of skull opening sizes are used to evaluate their outcome in DC surgery for brain tissue swelling in ischaemic stroke and its complications. This mathematical modeling concept hopefully can be used as prediction strategy into the application of DC for the treatment of ischaemic stroke.

2 Methodology

2.1 Mathematical Model

The swelling of brain tissue formed due to prolonged ischaemic period has been developed by applying filtration of capillary model and equation of poroelastic [6]. The tissue of brain is assumed as an isotropic poroelastic material, which contains of a solid tissue matrix permeated by interstitial fluid and the process of swelling takes place with little amount of strain. The poroelastic model has following equation:

$$\nabla \cdot \sigma_{ij} - \alpha_w \nabla P_w = 0 \quad (1)$$

where the term σ_{ij} is the tissue stress total, P_w is the pressure of interstitial water, α_w is the Biot parameter of water. This equation defined relationship between the stress

of brain tissue and ICP. The equation of interstitial fluid pressure distribution of is as follow:

$$\frac{1}{Q_w} \frac{\partial P_w}{\partial t} - k_w \nabla^2 P_w - S_{b \rightarrow w} = 0 \quad (2)$$

where Q_w known as the relative compressibility of water, t is the time while k_w is water permeability in porous tissue. Meanwhile, net flow of water into the tissue of brain from space of capillary due to capillary filtration is defined as term of $S_{b \rightarrow w}$. the filtration of capillary is assumed to take place after ischaemic stroke, in which cause by break down of a specialized layer called blood brain barrier (BBB). As a result, particles such as tiny proteins and ions to travel across this layer and accumulate in the extracellular space of brain tissue. The accumulations may cause the water to enter the extracellular space of brain tissue from reperfused blood, which cause swelling of tissue.

σ_{ij} , total stress is linearly correlated to the strain, ε_{ij} , as given by:

$$\sigma_{ij} = 2G\varepsilon_{ij} + \frac{2G\nu}{1-2\nu} \varepsilon_{ii} \quad (3)$$

G is the shear modulus, meanwhile ν is the Poisson's ratio of brain tissue and it has been shown that they play significant roles in the progression of brain swelling [7]. The strain and the displacement of tissue, u_i , are then related, in which associated to the following relationship:

$$\varepsilon_{ij} = \frac{1}{2} (\nabla u_i + \nabla u_j) \quad (4)$$

Meanwhile, $S_{b \rightarrow w}$ term is given below:

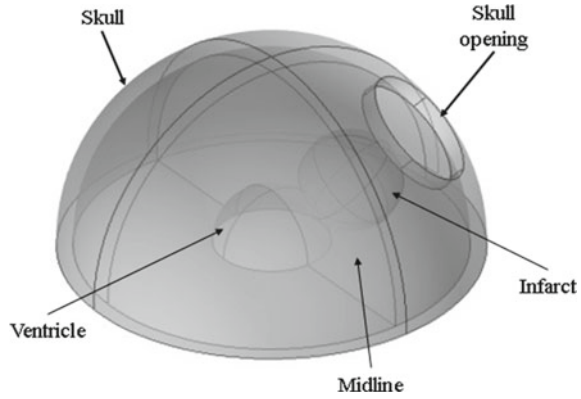
$$S_{b \rightarrow w} = 2\bar{n}_b \frac{L_p}{R_c} f[(P_b - P_w) - \sigma \Pi_b] \quad (5)$$

where \bar{n}_b is blood fraction baseline volume, L_p is capillary hydraulic permeability, R_c is capillary radius baseline value, σ is the coefficient of reflection, Π_b known as pressure of osmotic in the capillary meanwhile P_b is presumed as a constant, which known to be pressure of blood. Finally, f term indicates as capillaries ratio that maintain open after process of swelling and ischaemia-reperfusion at exact point in space and time.

2.2 Idealized 3D Brain Model

The idealized of brain geometry model, shown in Fig. 1, is developed based on spherical shape suggested by [8]. The brain model is developed by a half sphere

Fig. 1 The idealized 3D brain model



with a hole of half spherical at the center, which indicating the lateral ventricles. Another sphere is constructed within the geometry of half spherical to indicate the infarct of ischaemic. Then, 3D brain model is layered by another half spherical with an opening to represent the skull geometry with DC surgery.

The radius of brain, ventricle and infarct are set to be 80 mm, 24 mm and 14 mm respectively. Meanwhile, to evaluate the opening skull size outcome on DC surgery, the opening skull sizes are varied of 10, 15, 25 and 30 mm.

2.3 Numerical Procedure

The idealized 3D brain model is simulated using finite element software named COMSOL Multiphysic 5.3a. In this simulation, the skull has Young’s modulus and Poisson’s ratio, described based on Table 1. Meanwhile, the tissue of brain has separate material properties, in which also listed in Table 1 [6].

Boundary Condition. To allow for the outcome of brain tissue swelling on the ventricle movement, the ventricle, R_v , has been set to be moved freely by setting the total stress on the tissue, σ_{ij} on ventricle as follows:

$$\sigma_{ij}(R_v, t) \cdot n = -P_w(R_v, 0)n \tag{6}$$

Initial Conditions. Initially, the pressure of interstitial fluid, P_w and the displacement of tissue u are set at baseline \bar{P} and zero, as follow:

$$u(x, 0) = 0 \tag{7}$$

$$P_w(x, 0) = \bar{P} \tag{8}$$

Table 1 Parameter's list

Parameter	Name	Value
Poisson's ratio	ν	0.35
Young's modulus	E_T	2010 Pa
Permeability of brain	K_w	$1.4 \times 10^{-14} \text{ m}^2$
Water viscosity	μ_w	$1 \times 10^{-5} \text{ Pa s}$
Water Biot parameter	α_w	1
Water relative compressibility	Q_w	3244 Pa
Hydraulic permeability	L_p	$3 \times 10^{-11} \text{ m/s Pa}$
Reflection coefficient	σ	0.93
Pressure of osmotic in capillary	Π_b	2445 Pa
Pressure of blood	\bar{P}_b	4389 Pa
Pressure baseline value	\bar{P}	1330 Pa
Radius of typical capillary	R_c	$5 \times 10^{-6} \text{ m}$
Stiffness of capillary wall	E	864.5 Pa
Blood volume fraction baseline value	\bar{n}_b	0.03
Fraction of volume water	n_b	0.8
Young's modulus (Skull)	E_s	$3.15 \times 10^6 \text{ Pa}$
Poisson's ratio (Skull)	ν_s	0.45

Mesh Element Size. 10-node tetrahedral elements are used to mesh all geometries. Meanwhile, number of elements are varied in within 16,000–19,000. The ischaemic infarct has finer meshes than rest of geometry.

3 Results and Discussion

A simulation of an idealized 3D brain model was performed to evaluate the outcome of DC surgery using different size of skull opening in reducing the midline shift after 5 h of ischaemia–reperfusion. For a simple visualization, the simulation results displayed below based on part of brain that been sliced half through infarcts and skull opening, in which take part at the brain geometry centre.

Figure 2 shows the displacement of tissue of brain for infarct radius of 14 mm with different skull opening sizes. Midline shift that takes place in the middle of ventricle is also known as the brain herniation. In clinical study, brain herniation is used as indicator to predict the severity of brain tissue swelling in stroke [9, 10]. Based on Fig. 2, skull opening size of 30 mm experiences the least herniation compared to the skull opening of 10, 15 and 25 mm of skull opening size. This is because the skull opening causes the reduction of ventricle compression by allowing the brain tissue to swell towards the opening. Even though DC surgery has been proven to reduce

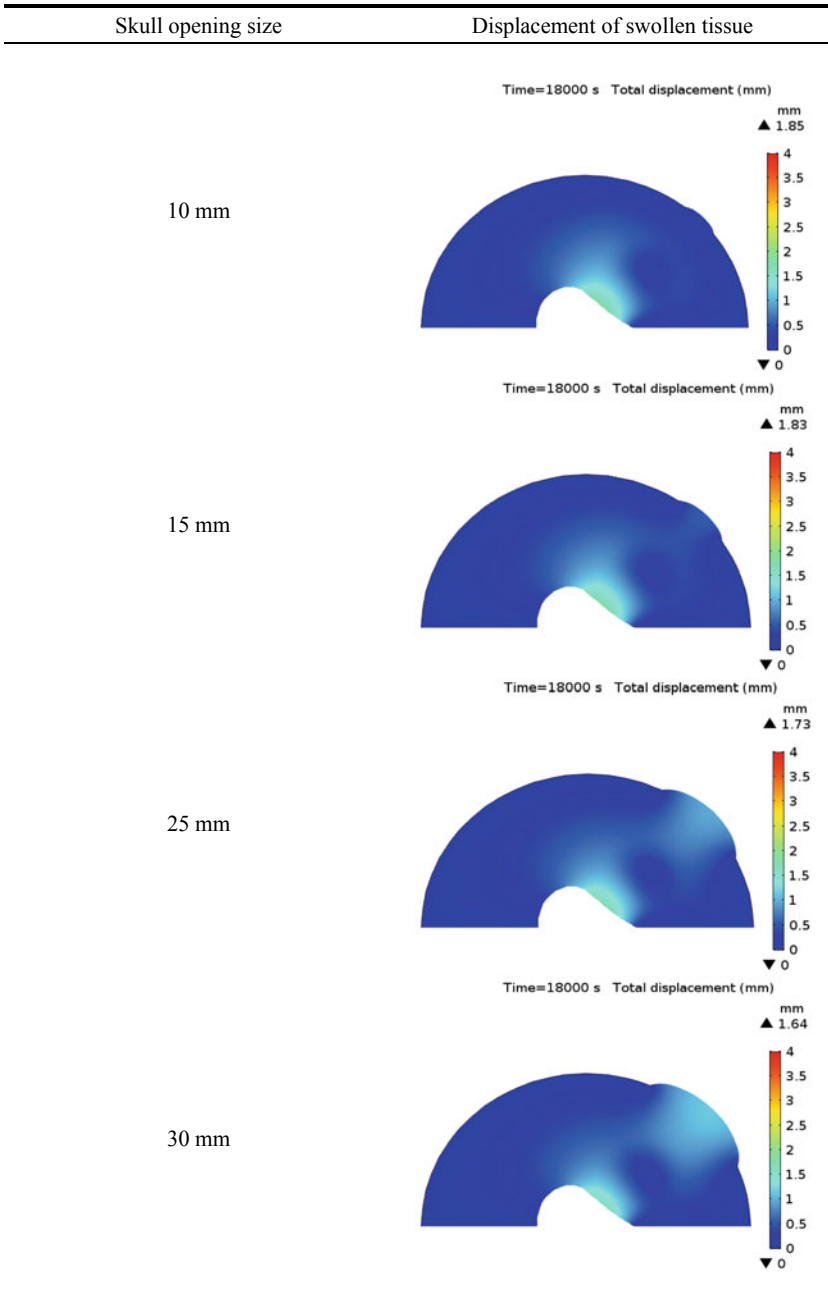


Fig. 2 The displacement of midline shifted with varies size of opening skull

the elevation of ICP [11] in brain as well as to reduce herniation, this surgery may also contribute some complications that still need to be considered.

Further, Fig. 3 shows that the skull opening size of 10 mm experience major stress in between the opening edges and brain tissue. This is because, small skull opening size increases the compression at the opening edges and also due to high brain tissue strain to bulge out from the skull. This may increase the risk of brain tissue damaged and infections [12].

Meanwhile, the largest skull opening size of 30 mm shows a much higher stress in between the edges of DC opening. Although the larger size of opening reduce the herniation, it may increase the risk of hydrocephalus development [1]. The more the swollen tissue bulged out from the skull, the higher the stress at the area of contact in between the edges of the opening and brain tissue [11]. Too large portion of skull being removed may result in an increase of rate of infections. The DC treatment for brain tissue swelling is still incomplete understood in reducing the severity of the swelling. Based on the findings obtained through this simulation, the larger craniectomy size may improve outcome, however it may also contribute to other complications such as risk of tissue damage, which is observed by the high tissue stress at the opening.

4 Conclusion

In conclusion, the mathematical model developed in this paper can assist the clinicians to obtain related surgical decision before performing the DC surgery on patients with brain tissue swelling due to ischaemic stroke. In our simulation the craniectomy model is developed to show how craniectomy size in DC may affect the brain herniation and complications that may occur after surgery as the treatment for swelling of brain tissue after ischaemia–reperfusion injury in stroke. Further investigation on the effect of ICP during DC surgery can be done to further understanding the efficacy of this treatment.

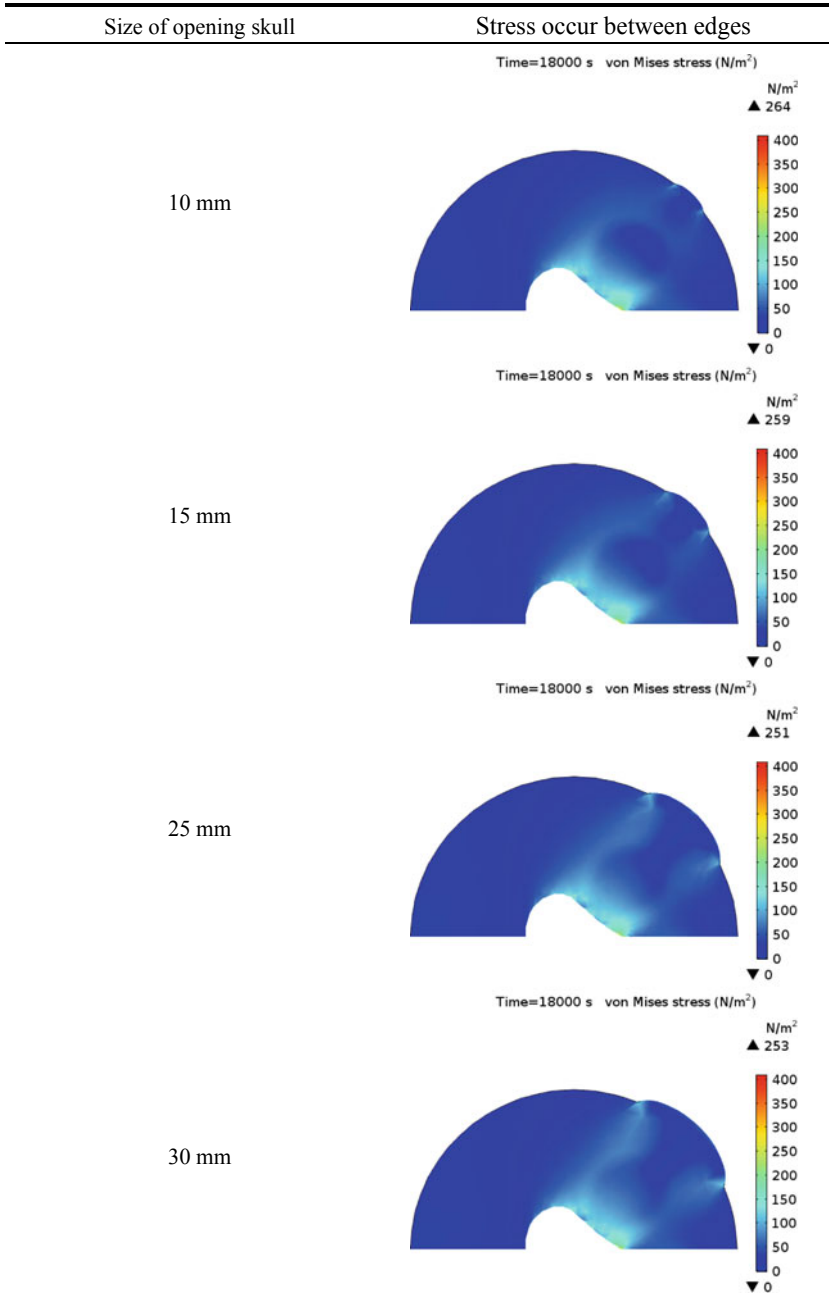


Fig. 3 The stress occur between the edges of opening skull

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