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Short communication

Biomechanical analysis of fluid percussion model of brain injury

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ABSTRACT

Fluid percussion injury (FPI) is a widely used experimental model for studying traumatic brain injury (TBI). However, little is known about how the brain mechanically responds to fluid impacts and how the mechanical pressures/strains of the brain correlate to subsequent brain damage for rodents during FPI. Hence, we developed a numerical approach to simulate FPI experiments on rats and characterize rat brain pressure/strain responses at a high resolution. A previous rat brain model was improved with a new hexahedral elements-based skull model and a new cerebrospinal fluid (CSF) layer. We validated the numerical model against experimentally measured pressures from FPI. Our results indicated that brain tissues under FPI experienced high pressures, which were slightly lower (10–20%) than input saline pressure. Interestingly, FPI was a mixed focus- and diffuse-type injury model with highest strains (12%) being concentrated in the ipsilateral cortex under the fluid-impact site and diffuse strains (5–10%) being spread to the entire brain, which was different from controlled cortical impact in which high strains decreased gradually away from the impact site.

1. Introduction

Traumatic brain injury (TBI) still remains a serious issue for society. To better understand TBI, various laboratory animal brain injury experimental models have been developed (Xiong et al., 2013) with weight drop (Marmarou et al., 1994), controlled cortical impact (CCI) (Dixon et al., 1991; Lighthall, 1988), and fluid percussion injury (FPI) (Dixon et al., 1987; Thompson et al., 2005) among the most widely used ones. For these neurotrauma experiments, one of the main research challenges is to understand how the brain mechanically responds to impacts and how the mechanical stresses/strains of the brain induce and correlate to subsequent brain damage. Especially for the rodent brain, which is small in size, experimental observations of live brain responses, especially brain deformation, are limited.

Brain responses during FPI remain largely unknown. For weight drop experiments, there are literature studies that combine experimental measurements of rat head kinematics and development of a finite element (FE) rat head model to analyze brain strain/stress responses and their correlations to axonal injury (Li et al., 2011a,b). For CCI, we have used a validated rat brain model (Mao et al., 2006) and quantitatively analyzed how different impact depth, velocity, impactor size, impactor shape, and craniotomy affect brain strains (Mao et al., 2010). Understanding brain biomechanics of CCI helped researchers develop new experimental setting that better mimic real-world mild TBI in laboratory (Chen et al., 2014). However, to the best of our knowledge, there is no computational simulation using FE method to elicit brain responses during FPI.

There is one study that uses a physical model to understand brain deformations during FPI. Thibault et al. filled soft gel materials into cadaveric cat skulls and observed brain deformations during FPI (Thibault et al., 1992). They reported that high strains were in the region of brainstem and that strains in other brain regions were negligible. However, caution must be practiced when attempting to postulate rodent brain deformations using Thibault's work, because the size and shape of animal heads are different and the gel material could influence strain values.

Our study is to develop a numerical approach to simulate FPI on rats and understand rat brain stress/strain responses at a high resolution. To do this, we improved our previous rat brain model with a new hexahedral elements-based skull model and a new fluid (CSF) layer. We validated the numerical model against experimentally measured pressures from FPI (Clausen and Hillered, 2005), and comprehensively analyzed regional strain and intracranial pressure responses.

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Nomenclature

CCI	controlled cortical impact	FPI	fluid percussion injury
CSF	cerebrospinal fluid	TBI	traumatic brain injury
FE	finite element		

2. Methods

2.1. Fluid percussion experiment

Clausen and Hillered (2005) performed FPI experiments (Fig. 1a) and applied pressurized saline to the brain. The intracranial pressure was measured using pressure probes with a diameter of 0.25 mm (Fig. 1b). The frequency of data recording was 500 Hz.

2.2. Simulation of fluid percussion experiment

A previously developed finite element (FE) rat brain model (Mao et al., 2006) was improved by incorporating a layer of cerebrospinal fluid (CSF) determined from MRI scans of four Sprague Dawley adult rats. Furthermore, one-layer rigid shell elements of the skull were improved as three-layer solid elements, representing the inner cortical bone, middle cancellous bone, and outer cortical bone. The similar three-layer skull model was used for the human head model (Mao et al., 2013). We justified that a deformable skull model was needed to allow realistic skull deformation. A density of 1500 kg/m^3 was assigned for the skull and Young's modulus of 13.5 GPa and 1.0 GPa were assigned to cortical and trabecular bone layers, respectively. These moduli were assumed based on our previous experimental studies on rat skull material property (Mao et al., 2011). Brain material properties remain same as our previous descriptions (Mao et al., 2006). The rat brain model included major brain components such as the cortex, corpus callosum, hippocampus, thalamus, cerebellum, and brainstem, represented by hexahedral elements. More detailed information about the rat brain model could be found from our previous publications (Mao et al., 2006; Mao and Yang, 2011).

A Gruneisen equation of state (Tutt and Taylor, 2008) shown below (Eq. (1) was adopted to simulate the pressurized saline with peak values of 2.6–2.9 atm (Clausen and Hillered, 2005).

$$p = \frac{\rho_0 C^2 \mu[1 + (1 - \frac{\gamma_0}{2})\mu - \frac{a}{2}\mu^2]}{[1 - (S_1 - 1)\mu - S_2 \frac{\mu^2}{\mu+1} - S_3 \frac{\mu^3}{(\mu+1)^2}]^2} + (\gamma_0 + a\mu)E \quad (1)$$

where C is the intercept of shock velocity to particle velocity curve, S1, S2, and S3 are three unitless coefficients, γ_0 is unitless Gruneisen gamma, and $a$is the first-order volume correction to γ_0. C, S1, S2, S3, and $\gamma_0$were defined as 1647 m/s, 1.921, 0, 0, and 0.35, respectively.

Fluid-solid interaction was implemented between the saline and brain through sharing nodes using a commercially available software LS-DYNA (LSTC, Livermore, CA). The position and size of the craniotomy was defined according to the experiment setting.

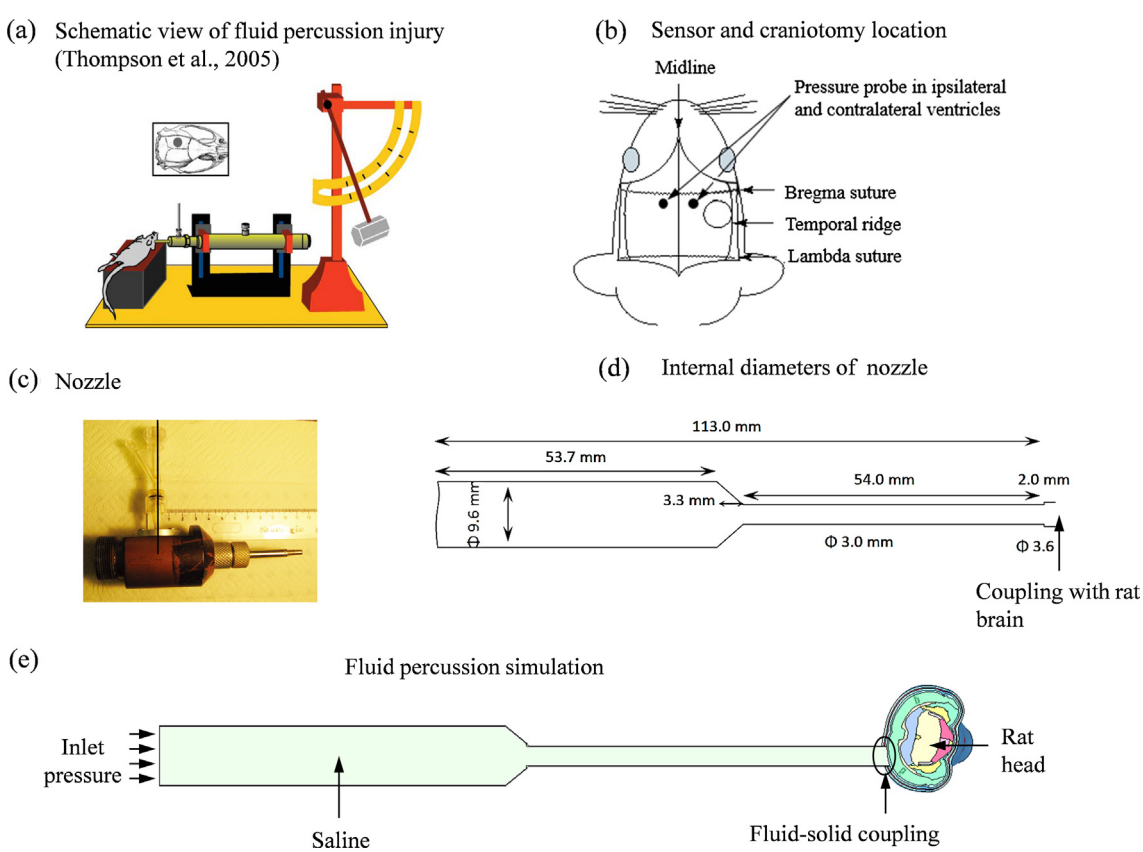

Fig. 1. Experimental setting of fluid percussion experiments and simulation. (a) A schematic view showing fluid percussion injury; (b) Descriptions of locations of craniotomy and sensor. (c) Photo of the nozzle; (d) Mechanical drawing of the internal dimensions of the nozzle; (e) Simulation of the nozzle and rat head.

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