Chapter 2
Dynamic Response and Damage Estimation of Infant Brain for Vibration

Takayuki Koizumi, Nobutaka Tsujiuchi, Keisuke Hara, and Yusuke Miyazaki

Abstract The purpose of this paper is to clarify the mechanical generation mechanism of acute subdual hematoma, which is a severe injury in infants, by performing experiments and finite element analysis. The acute subdural hematoma in infants is caused by accidents such as falling or abuse such as shaking. This paper describes the shaking events.

In the experiments, we used a 6-month-old anthropometric dummy and a vibration exciter, which can set the parameters. The dummy was fixed to the exciter at the chest, which it was given the vibration. The head model of the dummy is transparent, and the brain behavior can be visualized. In finite element analysis, we used a model that has been converted to the 6-month-old head through the adult head by the method of free-form deformation (FFD) and scaling. Also, we performed the simulation of shaking events as input acceleration and angular velocity of the head obtained in the experiments.

We measured the stretch ratio of the bridging veins, which connect the skull and the brain, then compared this with the ratio to the threshold (1.5). In this study, we examined the effect on the infant head of shaking action, along with the risk.

Keywords Infant • Acute subdural hematoma (ASDH) • Shaken baby syndrome • Finite element analysis • Material properties • Frequency

2.1 Introduction

Currently in Japan, the leading cause of death in children under a year old is accident, and this has not changed since 1960 [1]. Intentional injury such as abuse experienced by children has also become a problem, and physical abuse involving infant head trauma is considered the highest risk to life.

Among severe cases of infant head trauma, acute subdural hematoma (ASDH) is prominent. The mortality rate due to this is high, and the survivors suffer from heavy permanent damage. When assessing ASDH, it is not easy to ascertain whether its cause is abuse by shaking or an accident such as a fall. Judgment of abuse or accident in medical institutions that relies on experience and intuition lacks a scientific basis. Shaken baby syndrome is well known as a form of head injury caused by abuse. However, it is not clear whether the shaking action itself is fatal from previous study. Therefore, it is necessary to clarify the generating mechanism of ASDH in infants and to provide a scientific basis to make the judgment.

ASDH occurs by the relative rotational motion between the skull and the brain with a rupture of bridging veins. However, with the traditional dummy that has a rigid head, it is not possible to visualize the relative rotational motion between the skull and brain during shaking.

Therefore, in this study, we use an infant anthropometric dummy that has a realistically shaped physical model of an infant head to visualize the relative motion between the skull and the brain. Also, we perform experiments to evaluate the

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behavior of the dummy head for vibration input that assumes a shaking act with a vibration exciter. The vibration exciter can set the parameters such as frequency and amplitude.

In addition, we constructed a finite element model of the infant head and simulated the shaking. The model faithfully reproduced the shape. By performing the simulation, we examined the stretch ratio of the bridging veins and relative motion between the brain and skull when shaking.

2.2 Anthropometric Dummy

2.2.1 Six-Month-Old Anthropometric Test Dummy

In this experiment, we used a CRABI 6-month-old (CRABI 6-Mo) [2], whose height is 67 cm and weight is 7.8 kg. The neck is shaped in soft rubber, and attributes such as bending and stretching are close to the actual biology. The dummy reproduced the highest biological characteristics of the infant in current commercial dummies. The x axis is aligned in the anterior posterior direction, with positive x indicating the anterior direction. The y axis is aligned in the lateral directions, with the positive y indicating the dummy's left side. The z axis is aligned in the superior–inferior direction, with positive z indicating the superior direction.

2.2.2 Transparent Skull Model

In this study, we used the transparent skull model to visualize the behavior of the brain [3]. Figure 2.1 shows the model. This model reproduces the shape of the head of an infant. The skull is composed of polycarbonate with high transmittance. The brain model is composed of left and right cerebrum, cerebellum and brain stem, and manufactured with silicon gel, the dynamic viscoelastic properties of which are equivalent to the real brain. This brain model was inserted into the skull model and then the gap between brain and skull was filled with water as cerebrospinal fluid (CSF). Flax and tentorium were modeled with a polyurethane sheet, the Young's modulus of which was equivalent to the real one; then it was affixed to the inner surface of the skull. Thus, the brain movement was confined.

We constructed the infant dummy, which can visualize brain behavior, by attaching the transparent skull model to CRABI 6-Mo. Figure 2.2 shows the dummy.

2.3 Experiments

The shaking vibration by humans is not constant. Therefore, in this study, we performed the experiments using a vibration exciter to set the input parameters such as frequency and amplitude.

Fig. 2.1 Head physical model

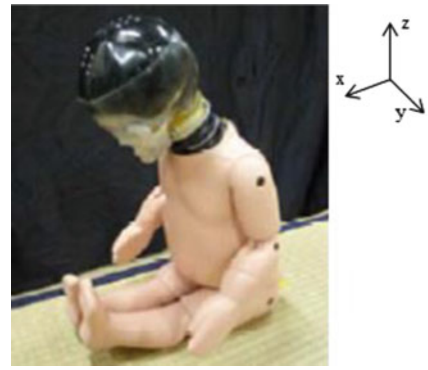

Fig. 2.2 Infant dummy (CRABI 6-Mo)

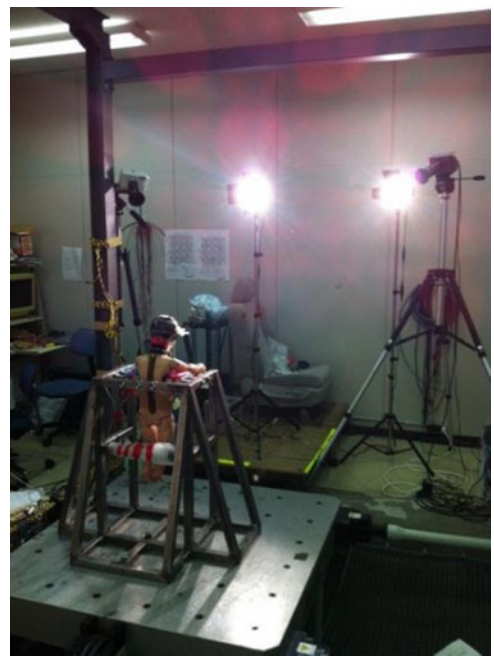

Fig. 2.3 Appearance of shaking experiment by vibration exciter

2.3.1 Methods

Figure 2.3 shows the experiment aspect. The dummy was fixed on a board it was to transmit vibration of the vibration exciter to the chest. We set up an angular velocity sensor and acceleration sensors on the head of the dummy and attached an acceleration sensor on the chest; then, we measured the acceleration and angular velocity. We applied white markers to the inner surface of the skull and the brain surface to measure the relative movement between the skull and brain. We set to bv1-bv3 each combination of markers of brain and skull. Figure 2.4 shows the combination of markers. Head behavior was taken at a sampling rate of 500 fps or 200 fps with two high-speed cameras (D-III: Detect). The displacement time history of markers was measured by the digital image correlation method. Then, we measured the relative displacement of the markers of bv1-bv3 by converting the three-dimensional displacement method using the Direct Linear Transformation (DLT) method. In addition, we smoothed each three-dimensional displacement by the three-point moving average method. We calculated the stretch ratio (λ) between two points as the evaluation strain parameters of bridging veins of the attached positions by the three-dimensional displacement. The stretch ratio (λ) is defined by the following equation using the distance (l_0) of the bv1-bv3 in the video frame and the distance (l) of the bv1-bv3 in the initial position. We defined the value obtained by the following equation as the bridging vein stretch ratio.

$$\lambda = \frac{l}{l_0}$$

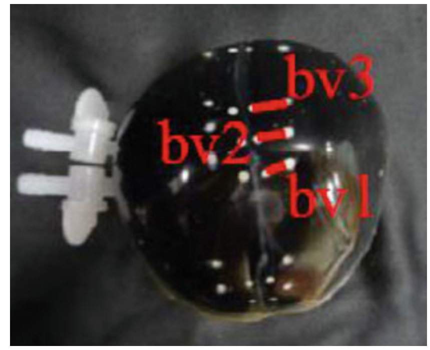

Fig. 2.4 Makers positions

2.3.2 Input Vibration

In previous studies, we concluded that the vibration in the vertical direction has less impact on the infant head. Therefore, we have performed experiments for only the X axial, which is the main component of the shaking vibration. Input vibrations were a total of 12 patterns, combining 3 amplitude patterns [30.0 mm, 40.0 mm, 50.0 mm] in the X axial with 4 frequency patterns [1.5 Hz, 2.0 Hz, 2.5 Hz, 3.0 Hz].

To reproduce the human act of shaking infants, input amplitudes are set to the value around the one with which people shake the infant dummy. In addition, input frequencies were set at a lower value than the maximum high-risk frequency (around 3.0 Hz) obtained by previous studies. In the previous study, the dummy's head, which was a rigid model, was swung the most on the 3.0-Hz frequency.

2.4 Results and Discussion

Results are reported in Fig. 2.5 in terms of the bridging vein stretch ratio of bv1-bv3 obtained by the experiments and time history and in Fig. 2.6 in terms of the maximum ratio of results and amplitudes.

The maximum of the bridging vein stretch ratio tends to increase with the increasing amplitude at any frequency in Fig. 2.6. Therefore, the breaking risk of bridging veins is high as amplitude increases.

For 40 mm or more amplitude on 3.0-Hz frequency, the stretch ratio exceeds the 1.5 threshold, which is the breaking value of bridging veins reported by Lee and others [4]. Particularly, for 50.0-mm amplitude, the stretch ratio is significantly higher than the threshold. For 30.0-mm amplitude, the stretch ratio is significantly below the threshold even though the frequency is 3.0 Hz, which is high-risk. Therefore, bridging veins are likely to break above 40.0-mm amplitude on 3.0-Hz frequency, and the risk is especially high in 50.0-mm amplitude, while there is no risk in 30.0 mm amplitude. In other words, we can prove mechanically that ASDH is likely to occur for severe vibration.

In Fig. 2.6, the stretch ratio is significantly below the threshold in any amplitude of 2.5 Hz and under. In other words, bridging veins don't break for 2.5 Hz and under. Therefore, we can conclude that ASDH due to breaking bridging veins does not occur with the vibrations resulting from cradling.

2.5 Simulation

2.5.1 Construction of Model and Material Properties

The finite element model of an infant head has been developed very little, even though the head model of adults has been developed in many studies. For constructing a finite element model of the infant head, it is not appropriate to obtain it from scaling the adult head model. A highly accurate infant head model cannot be constructed because the characteristics of skull shape are different for infants and adults.

In this study, we used the finite element model of a 6-month-old head, which is newly constructed. Figure 2.7 shows the new model and Table 2.1 shows the dimensions. We retrieved the three-dimensional shape date of the head by CT images of a

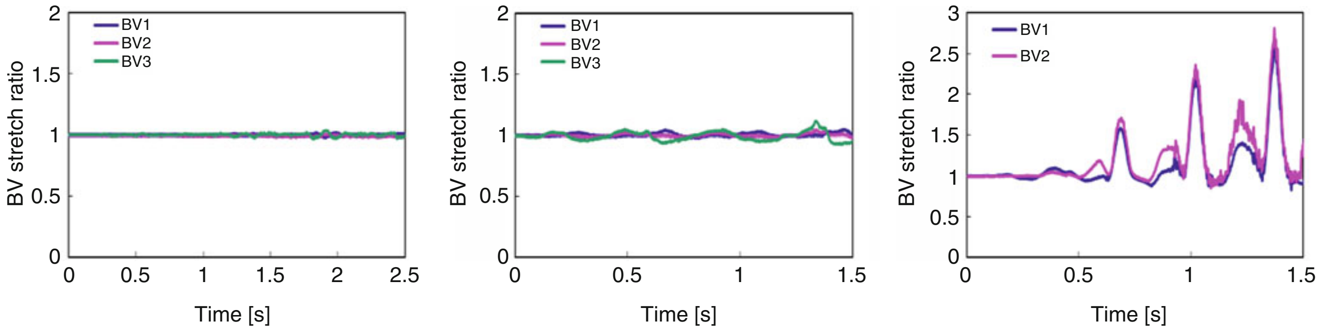

Fig. 2.5 Bridging vein stretch ratio responses with high speed camera images

Fig. 2.6 Max bridging vein stretch ratio responses with high speed camera images

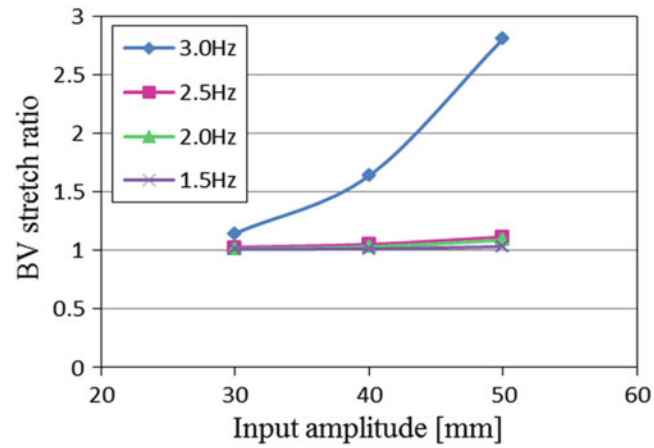

Fig. 2.7 Finite element model

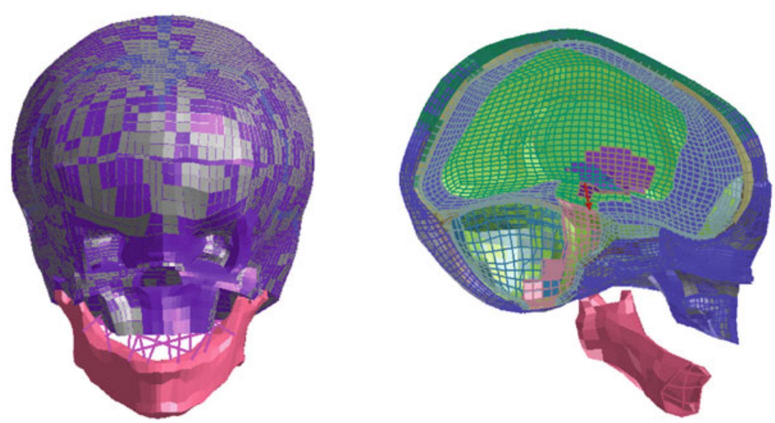

Table 2.1 Dimension of 6-Mo head [mm]

Length	Breath	Height
154.9	119.4	147.3

particular 4-month-old head. Then, we converted the shape of the finite element model of an adult head into the 4-month-old head model based on the shape date with the free-form deformation transformation (FFD) method. The 6-month-old infant head finite element model that is used in this study is constructed by scaling the dimensions of a 4-month-old head which have been converted to the shape of the CRABI 6-Mo head.

The head finite element model is composed of a skull including structure and anterior fontanel, cerebrospinal fluid (CSF), brain (left and right cerebrum, cerebellum and brainstem), and membrane (dura mater, pia mater, flax and tentorium).

Table 2.2 Material properties (1)

Part	Material property	Density ρ [kg/m^3]	Young's modulus E [GPa]	Poisson's ratio ν
Right cerebrum	Linear_Visco_Elastic	1,040	K = 2.19	
Left cerebrum				
Cerebellum				
Brain stem				
Pia mater	Elastic	1,133	1.15×10^{-2}	0.45
Dura mater		1,133	3.15×10^{-2}	0.45
Falx		1,133	3.15×10^{-2}	0.45
Tentorium		1,133	3.15×10^{-2}	0.45
Sagittal sinus		1,133	3.15×10^{-2}	0.45
CSF	Linear_Visco_Elastic	1,060	K = 2.19	
Ventricle				
Skull diploe	Elastic	2,150	421×10^{-3}	0.22
Structure			4.2×10^{-3}	
Mandible	Elastic	2,150	4.6	0.05
Inner table	Elastic	2,723	15	0.21
Outer table				
Bridging vein	Elastic	1,133	9.62×10^{-3}	0.45

Table 2.3 Material properties (2)

Part	Density [kg/m^3]	Bulk modulus [Gpa]	Short time shear modulus [GPa]	Long time shear modulus [GPa]	Decay constant [s^{-1}]
Brain	1,040	2.19	$2{,}710 \times 10^{-9}$	891×10^{-9}	166
CSF	1,060	2.19	500	5.0×10^{-7}	500,000
Ventricle					

Table 2.4 Properties of the modified material (1)

Part	Material property	Density ρ [kg/m^3]	Young's modulus E [GPa]	Poisson's ratio ν
Brain	Linear_Visco_Elastic	1,040	K = 2.19	
Falx	Elastic	1,133	3.15×10^{-2}	0.45
Tentorium		1,133	3.15×10^{-2}	0.45
Skull	Elastic	1,200	2.45	0.33

Table 2.5 Properties of the modified material (2)

Part	Density [kg/m^3]	Bulk modulus [Gpa]	Short time shear modulus [GPa]	Long time shear modulus [GPa]	Decay constant [s^{-1}]
Brain	1,040	2.19	$2{,}704 \times 10^{-9}$	886×10^{-9}	166
CSF	1,060	2.19	500	5.0×10^{-7}	500,000

Tables 2.2 and 2.3 shows the material properties of each tissue. Suture and skulls of infants are soft as ossification is not complete compared with adults. Thus, the material properties used the average value of the measurement results of 1–12 months, which are obtained in the three-point bending test of Margulies et al. [5]. Material testing at 6 months has not been carried out. Therefore, the suture material property used is for 11 months. The CSF property used is a viscosity elastic property, almost like water. In addition, other properties given are the adult properties.

We can verify the operational state of the load and the deformation of the intimal structure such as skull and brain by using a finite element modal.

2.5.2 *Simulation and Result*

In this study, we have carried out a simulation to verify the frequency response of the brain. In the simulation, we constructed the finite element model of the dummy's head. We developed the model by modifying the material properties because the dummy's head and the finite element model are equal for shape and structure. The dummy's head is composed skull, brain, flax, tentorium and CSF. Therefore, the simulation model is standardized of dummy's configuration. Tables 2.4 and 2.5 shows the properties of the modified material.

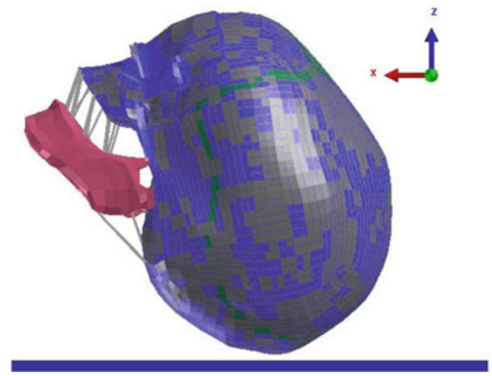

Fig. 2.8 Simulation condition

Table 2.6 Input values

Initial velocity (x) [m/s]	Initial velocity (z) [m/s]	Initial angler velocity (y) [rad/s]
2.86	−4.43	−27

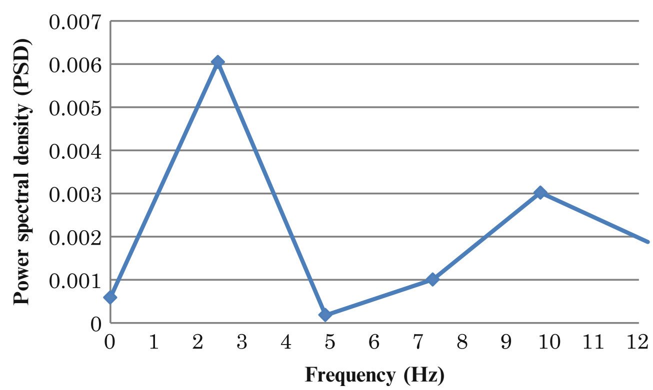

Fig. 2.9 Power spectral density obtained by FFT

We simulated the event of falling impact from the back head to ground with the simplified model of the above using the PAM_CRASH solver. The skull model was defined as rigid body and given a translational velocity and angular velocity when upset from 1 m high to the center of gravity position. And then, we examined the response of the elements of the brain surface. Figure 2.8 and Table 2.6 show the conditions of simulation.

As a result of the simulation, the resonant frequency is detected at around 2.5 Hz. Figure 2.9 shows the power spectral density, which is obtained by fast Fourier transform (FFT) of the acceleration obtained by simulation. In the experiment, it is found the 3.0 Hz vibration is the high risk to break the bridging veins for the infant head. Therefore, the brain of the infant will resonate between 2.5 and 3.0 Hz, and the vibration in this frequency band is dangerous to influence significantly the brain.

2.6 Conclusion

1. In the experiment, ASDH is likely to occur for severe vibration such as the frequency is 3.0 Hz and the amplitude is 50.0 mm. And also, ASDH due to breaking bridging veins does not occur with the vibrations resulting from cradling since bridging veins don't break for 2.5 Hz and under.
2. In the simulation, the resonant frequency is detected at around 2.5 Hz. Therefore, the resonant frequency of an 6-month-old brain is between 2.5 and 3.0 Hz, and it is dangerous to vibrate the infant in this frequency band.

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