Original Article

A Finite Element Analysis of the Retinal Hemorrhages Accompanied by Shaken Baby Syndrome / Abusive Head Trauma[☆]

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Abstract

We aimed to elucidate the mechanism of the retinal hemorrhage (RH) accompanied by shaken baby syndrome or abusive head trauma (SBS / AHT) by analyses using a computational model. We focused on a hypothesis that the vitreoretinal traction due to acceleration and deceleration caused by abusive shaking leads to retinal hemorrhage. A finite element (FE) mechanical model with simple spherical geometry was constructed. When the FE mechanical model was virtually shaken, the intensity of the stress applied to the retinal plane agreed well with the results from an analysis using a physical model made of agar gel. Impacts due to falling events induced more intensive tensile stresses, but with shorter duration, than the shake did. By applying a mathematical theory on tackiness, we propose a hypothesis that the time integration of the stress, in the unit of Pa·s, would be a good predictor of the RH accompanied by SBS / AHT. A single cycle of abusive shake amounted to 101 Pa·s of time integration of inflicted stress, while a single impact event amounted to 36 Pa·s. This would explain the paradoxical observation of that shaking induce RH while RH due to impact events is only seen in a major event such as a fatal motor vehicle accident.

1. Introduction

Shaken baby syndrome or abusive head trauma (SBS / AHT) is caused by violently shaking an infant with or without impacting on the head, and is characterized by serious brain and nerve damages including death. Along with damages such as subdural hematomas or diffuse axonal injuries, SBS / AHT is often accompanied by retinal hemorrhages (RH). RHs are empirically regarded as an important symptom to distinguish abuse from accident because it is seen in approximately 85% of the victims of SBS / AHT whereas it is observed under accidental context only with decisive external injuries such as those in fatal motor vehicle accidents (Wyganski-Jaffe et al., 2009). In contrast to the term SBS, the term AHT does not require shaking as a necessary factor, but shaking is still considered as a very major factor. It is important to elucidate the mechanism of the specificity of RH to SBS / AHT to establish a firm scientific basis for the recognition of abuse, which will hence contribute to its prevention.

A major volume inside the eyeball is filled with a tissue called vitreous body, a transparent and gel-like tissue placed behind the lens. The inner surface of the retina, the sensual tissue connected to the optic nerve, is directly attached to the vitreous body. The soft and delicate structure of the retina is supported by the sclera, a tough tissue maintaining the spherical shape of the eyeball. The sclera is also known as the white of the eye and forms the outermost layer of the eyeball together with the cornea. There lies a layer of tissue called choroid between the retina and the sclera, which supplies the retina with oxygen and nourishment through capillary network and also shuts out stray light with its pigmentation.

When an infant is subjected to violent shaking, several factors are hypothesized to be included in the occurrence of RHs, *e.g.* increased intracranial pressure, increased intrathoracic pressure and orbital injury. Among them, we focused on a hypothesis that the vitreoretinal traction due to acceleration and deceleration caused by the shaking leads to the damage of the retinal tissues because this factor is most feasible and attracting most attention (Morad et al., 2002).

Because detailed description of abusive events based on witnessing is very scarce, simulation analysis is necessary to verify clinical or autopsy findings. Animal experiments reproducing abusive settings are an important option to consider, but are with several inevitable problems, *e.g.* the difference in morphology and physical properties of animal models from human infants, the complexity and individual variability of animal models that may hinder the analytical process and the serious ethical concerns.

Computer simulation is a powerful tool to analyze the mechanism of this phenomenon because it is able to compensate for the limitations of the animal experiments. We have developed a finite element (FE) mechanical model to tackle this problem. This model is made by dividing the subject into numerous but finite solid and plate elements. Then the equations describing the elasticity of each element are computed simultaneously.

Two preceding papers have employed the FE method to analyze this problem (Rangarajan et al., 2009;

Hans et al., 2009), which concluded that the shaking could be responsible for the RHs in SBS / AHT. The models used in these studies contained parts based on medical images, and were elaborate and realistic. However, these studies suffered from an unexplained phenomenon termed as stress buildup (Rangarajan et al., 2009) or a significant level of noise (Hans et al., 2009). This is partly because these models were somewhat too complex, and thus ironically concealed the relation of cause and effect.

Therefore, we generated our model from scratch, assuming a simple spherical geometry. By giving up some extent of reality, we attempted to remove inessential factors for a clearer analysis. We examined the stress tensor in our analysis, instead of considering the von Mises stress, as in one of the preceding papers (Rangarajan et al., 2009). Von Mises stress is often used to describe the yield strength of hard materials used in machines or architectures, and is not necessarily applicable to the detachment between soft tissues as vitreous body and retina. On the other hand, tensile, compressive and shearing components of the stress with respect to the retinal plane can be extracted from the stress tensor, and their relevances to RH can be discussed separately.

Yamazaki et al. (2014) pointed out the importance of the time integral of stress in understanding the mechanism of RH in SBS / AHT, through a study using a dummy doll equipped with an eyeball model. We reconstructed this eyeball model as an FE mechanical model to further examine this idea. While only the normal component of the stress was obtained from the measurements in Yamazaki et al. (2014), the whole stress tensor is available from the computational analysis.

2. Methods

2.1. General structure of the computational model

We constructed a simple computational model of an eyeball for FE mechanical analysis that included the vitreous body, the cornea, the sclera, the fatty tissue and the orbit (Fig. 1). Our model is with controllable numerical precision and is easily modified because it is fully automatically generated by a Fortran95 program (Supplementary material 1). This FE mechanical model was analyzed using a computer-aided engineering platform (HyperWorks Version 11.0, Altair Engineering, Inc., Troy, MI, USA). The spherical shape of the vitreous body had a cubic core, surrounded by six peripheral shapes attached on each side of the cube. This sphere was covered with the sclerocorneal membrane. This eyeball was further wrapped with a layer of fatty tissue. The anterior part of the fatty tissue was absent to reproduce eye opening. The layer of the fatty tissue is then covered with a cortical bony layer representing the orbit. All of the adjacent elements shared common nodes. The vitreous body and the fatty tissue were modeled with hexahedral solid elements; the cornea, the sclera and the orbit were modeled with tetragonal plate elements.

2.2. Dimensions and physical properties of the computational model

The radius of the eyeball and the orbit were set to 10 mm and 16 mm, respectively, and the thickness of the cornea, the sclera and the orbit were all set to 1 mm (Rangarajan et al., 2009). Mass densities of all materials were set to 1 g / mL. Poisson’s ratios of all materials were set to 0.5, which means all materials were incompressive. The Young’s moduli of each material were cited from the literature: the cornea, *ca.* 10 MPa (Wang et al., 1996); and the sclera, 310 MPa (Uchio et al., 1999). The orbit was considered as a rigid body. The Young’s modulus of the fatty tissue was set within the average range of soft-tissue properties of humans, 47 kPa, as in Todd and Thacker (1994). The Young’s modulus of 1.9 kPa, that of 0.5% agar, was employed to simulate the mechanical property of the vitreous body of infants, and the Young’s modulus of 30.3 kPa, that of 1.0% agar, was also used for comparison (Yamazaki et al., 2014). All of the elastic materials used in the FE mechanical model were isotropic and assumed linear relation between stress and strain, *i.e.* Hooke’s law.

2.3. Analysis of the stress tensor

The very thin membranous structures of the retina and the choroid were not explicitly reproduced in our model. Alternatively, we considered the outermost elements of the vitreous body as representing the mechanical state in the vicinity of the retina. The components of stress tensors were retrieved from the simulation results using a Tcl/Tk script (Supplementary material 2), while the coordinate system of the stress tensor was transformed to one tangential to the retinal plane and orthogonal to the local latitudinal and longitudinal axes.

2.4. Digitizing violent shaking by an imitate perpetrator

The data were cited from a previous study (Yamazaki et al., 2014). A doll simulating a one-month-old infant was shook by an imitate perpetrator to obtain data of violent shaking and its effect on the fundus of the eyeball. This doll was also subjected to a free falling of 50-cm high to a hard floor. This doll was equipped with an eyeball model, which had a plastic shell filled with agar gel simulating the vitreous body. The neck of the doll only tethered the head to the body, similarly as a newborn infant. Shaking was monitored with an accelerometer set on the head of the doll parallel to the sagittal axis, whose positive direction corresponded to the posterior direction of the doll, and was used as the input to virtually move the computational FE model, which was initially at rest. The reproduced shaking movement was one-dimensional, straight along the z-axis, since only one accelerometer was used. The stress invoked by the shake at the fundus of the eyeball model was recorded by a pressure sensor, and used to verify the computational results.

3. Results

The eyeball model was sinusoidally shook in the computer simulation framework with a frequency of 2.5 Hz and a stroke of 30 cm along the sagittal axis, as a rough simulation of an abusive shake event. Two Young's moduli of the vitreous body were tested, *i.e.* 1.9 kPa and 30.3 kPa, corresponding to that of 0.5% and 1.0% agar gel model, respectively (Yamazaki et al., 2014). In a microscopic point of view, the retinal tissue may be exposed to either tensile, compressive or shear stresses. The tensile and compressive stresses are described by the component of the stress tensor normal to the retinal plane, while the shear stresses are denoted by the shear components parallel to the retinal plane. These components of the stress tensor are separately discussed in the following paragraphs.

The anteroposterior axis of the eyeball model coincided with the axis of simulated abusive shaking. The anterior side of the model was assumed to be facing the perpetrator shaking horizontally. Fig. 2 shows an instantaneous snapshot of latitudinal distribution of the components of the stress tensor in an eyeball subjected to this sinusoidal shake. This snapshot was taken at the moment when the eyeball was just beginning to be pushed away from the imitate perpetrator during a cycle of shake, when the intensity of the stress components came to a climax. The inconsistency between the forced movement of the surrounding sclerocorneal membrane and the inertia of the vitreous body was maximal at this moment. As mentioned in the Methods section, we focus on the stress tensor of the outermost elements of the vitreous body in our model, as they represent the mechanical state in the vicinity of the retina.

At the moment depicted in Fig. 2, tensile stresses were applied to the retinal plane in the posterior hemisphere, while the compressive stresses were applied in the anterior hemisphere. The shearing stress peaked in the equatorial area; the odd-shaped shoulders at $\pm 45^\circ$ seems to be artifacts probably due to the discontinuity of the model mesh. The intensity of the shearing stress was about two orders of magnitude minor than those of tensile or compressive stresses. Therefore, we suspect the tensile stress as the main cause that leads to major deformation of the tissue near the vitreoretinal attachment that leads to destruction of the capillary network and hence RH. This broadness of the stress application, together with the unpredictably wobbling nature of abusive shaking, will account for the broad and non-localized nature of RH in SBS / AHT, extending even to the ora serrata (Wynnski-Jaffe et al., 2009).

As a consequent outcome of that the axis of the simulated shake was strictly along the sagittal axis, which will probably never the case in actual abuse events, the most intensive tensile stress appeared precisely at the posterior pole when the eyeball is just pushed back during a cycle of a shake. By considering a simple shake of a simple model, we are able to locate the point exposed to the harshest stress and discuss the worst case. Thus, hereafter, we focus on the posterior pole, where the stress was most intensive.

The change of the component of the stress tensor normal to the retinal plane at the posterior pole along time is plotted in Fig. 3. The subtle difference in the response curves in spite of the 16-times difference

in the Young's moduli indicates that this physical property, difficult to measure (Nickerson et al., 2008), fortunately did not affect much the results.

Fig. 4 shows the simulated stress change due to an experimentally measured acceleration of the head of a shaken dummy doll cited from Yamazaki et al. (2014). The eyeball model was filled with 0.5% agar gel as a model of the vitreous body. Simulated and measured stress change at the posterior pole showed acceptable agreement to support the discussion below.

Fig. 5 shows the acceleration and stress change when this doll was subjected to an impact by falling from a 50-cm high to a hard floor, hitting in the front. As is intuitive, an intensive acceleration and stress change appeared in a very short time range, which is paradoxical to the experience of not causing RH in this kind of mechanical stress.

4. Discussion

We admit that we do not have any feasibility data to discuss the effect of vitreoretinal traction directly, which is the main target of criticism to FE studies of this kind (Margulies et al., 2009). Neither we reproduced detachment phenomenon in our model; all of the adjacent elements shared common nodes, which actually means that no detachment occurs in our simulation. However, comparing effects due to shaking and impact, apparently very different phenomena, in a same measure may give us an important insight described in the following paragraph.

A formula describing the tackiness based on a setting with a simple geometry has been provided (Bikerman, 1947). When two discs with a radius of a are bound with a layer of liquid adhesive of viscosity of η with a thickness of h_1 , the applied tensile stress denoted by F , the time duration of stress application denoted by t and the resultant thickness of the adhesive layer h_2 are related as follows;

$$Ft = \frac{3\eta a^2}{4} \left(\frac{1}{h_1^2} - \frac{1}{h_2^2} \right) \quad (1)$$

This formulation is based on that when a given region of a layer of adhesive thickens due to a tensile force, there must be a flow of adhesive material towards this region, parallel to the plane of the layer of adhesive material, to fill the extra volume required for the thickening. Since the left-hand side of Eq. 1 is proportional to time, this can be a good mechanical explanation of the term stress buildup, often used in this field without clear definition. That this formula includes a factor of viscosity, a property universal to liquid, supports the feasibility of this theory. Thus, according to this theory, time integration of the normal stress to the retina may be a good predictor of RH.

If we calculate this value for the shake shown in Fig. 4, 101 Pa·s per one cycle of shake is obtained. On the other hand, 36 Pa·s per one impact is calculated for the impact shown in Fig. 5. When the above values based on a mathematical model on the mechanism of adhesion were calculated from the areas of the graphs

of the stress changes, it was shown that the value of multiple round of shaking might readily surpass that of single impact. This may clearly explain why RH is characteristic to the shaking injury. Similar values are reported in the study using a dummy doll equipped with an eyeball model, which reported 107 Pa·s for a single cycle of abusive shaking and 60 to 73 Pa·s for a single event of fall, and reached the same conclusion (Yamazaki et al., 2014).

The classical theory on tackiness assumes the major origin of tackiness being the lateral flow of viscous fluid of adhesive material. This lateral flow of adhesive fluid between the vitreous body and the retina might be a more reasonable explanation for the pleated retinal folding than to attribute this to the effect of shear stress, which was shown to be about two orders of magnitude minor (Fig. 2). The counterpart compressive stress that appear in the opposite side of the cycle of shake will not contribute to the repair of the detachment of the adhesion because compressing by a soft matter such as the vitreous body itself will not be able to turn the unevenness of the viscous fluid layer back to the initial uniform distribution.

The strength of the vitreoretinal attachment is known to depend on the location; it is stronger in the surroundings of the macula and in the area approaching the ora serrata. We were not able to evaluate the effect of this factor since our model cannot reproduce detachment. That the shear stress is minor in the observed stress field in the eyeball imply that the effect of the strength of the attachment in a given region is restricted to a narrow vicinity in terms of longitude and latitude. Thus, the distribution of vitreoretinal attachment strength and the distribution of RH is not likely to be directly correlated. This coincides with the non-specific nature of the RH distribution.

As a rough estimation, we calculated thickening ratio (h_2/h_1) as a function of the initial thickness of the layer of liquid adhesive from Eq. 1 (Fig. 6). We compared the effect of a single event of impact ($Ft = 36$ Pa·s) and 10 cycles of shake ($Ft = 1010$ Pa·s). We assumed $\eta = 0.7$ mPa·s, simulating water under physiological temperature, and $a = 10$ mm. Fig. 6 shows that the thickening ratio as a result of 10 cycles of shake can be far greater than that as a result of single impact, when the initial thickness is above *ca.* $5 \mu\text{m}$. Although we are not able to specify the actual identity of the layer of liquid adhesive hypothesized in Eq. 1, the assumption of this layer with a thickness in the order of cell size at the vitreoretinal boundary may be not too far from reality, especially in the area without stronger vitreoretinal binding.

The FE mechanical model used in this study is simple yet retains essential features of real eyeballs adequate for the analysis. In this study, we have succeeded to develop a reasonable explanation for the paradoxical finding of RH in abusive context by keeping our model simple enough to clearly analyze the phenomenon based on a sound mechanical theory following a reliable chain of cause and effect. Our study may be too primitive in some aspects, but surely provides a firm basis for further analyses.

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Figure Legends

Figure 1: Visual representation of the structure of the computational eyeball model used in the FE analysis. The model is arbitrarily cut to illustrate the internal structure. The vitreous body (v) and the fatty tissue (f) were modeled with hexahedral solid elements; the cornea (c), the sclera (s) and the orbit (o) were modeled with tetragonal plate elements. The z-axis corresponds to the sagittal axis.

Figure 2: Latitudinal distribution of the components of the stress applied to the retinal plane. The component of the stress normal to the retinal plane is plotted with circles (left ordinate). Positive and negative values correspond to tensile and compressive stresses, respectively. The intensity of shearing stress applied to the retinal plane along the latitudinal direction is shown with triangles (right ordinate); that along the longitudinal direction was negligible and is not shown. The model contained a vitreous body with Young's modulus of 1.9 kPa. The abscissa shows the latitudinal angle; negative and positive poles correspond to the anterior and posterior poles, respectively. Note the difference in the scale between the two ordinates.

Figure 3: Changes of the normal stress applied to the retinal plane at the posterior pole during a simulated sinusoidal shake. The results using the model containing the vitreous body with Young's modulus of 1.9 kPa (a) and with 30.3 kPa (b) are shown (left ordinate). The models were virtually shaken with sinusoidal acceleration with a frequency of 2.5 Hz and a stroke of 30 cm (c, right ordinate, note the inverted scale).

Figure 4: Changes of the normal stress applied to the retinal plane at the posterior pole during a simulated shaking by an imitate perpetrator. The results from the computer model (a) and that from a pressure sensor set in the posterior pole of the eyeball model (b) are shown (left ordinate). The physically recorded acceleration change applied to the models (c) is also shown (right ordinate, note the inverted scale). Panels A and B correspond to the models containing the vitreous body with Young's modulus of 1.9 kPa and 30.3 kPa, respectively.

Figure 5: Changes of the stress applied to the retinal plane at the posterior pole during a simulated fall event from a 50-cm high to a hard floor, hitting in the front. Details are as in Fig. 4. Note the differences in the scales.

Figure 6: Predicted thickening ratio of the hypothesized layer of liquid adhesive in the vitreoretinal boundary. According to Eq. 1 roughly assuming physiological conditions, the resultant thickness of the layer as a result of single impact (solid curve) or 10 cycles of shake (dotted curve) are plotted.

Figure 1

Figure 2

Figure 3

Figure 4

A

B

Figure 5

A

B

Figure 6