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Summary

Determining the Tractional Forces on Vitreoretinal Interface Using a Computer Simulation Model in Abusive Head Trauma

Donny W Suh*

Truhlsen Eye Institute, University of Nebraska Medical Center, USA

The goal of this paper was to advance understanding of the pathophysiological process of vitreoretinal traction by determining the forces generated during shaking of an infant using the newly developed FE model. We hypothesized that a newly developed FE model could advance understanding of vitreoretinal traction in AHT by determining the forces on posterior ocular tissues during shaking of an infant.

Abusive Head Trauma (AHT) encompasses a form of inflicted head trauma in infants usually younger than two years of age. With or without blunt head trauma,AHT produces characteristic injuries to the central nervous system, cervical skeleton, and eyes, especially when the victim is subjected to repetitive acceleration and deceleration. AHT is the leading cause of infant mortality and long-term morbidity from injury. In most of these children, Retinal Hemorrhage (RH) demonstrates multifocal and multilayered involvement extending out to the ora serrata, with possible macular retinoschisis and vitreous hemorrhage. While the exact mechanism for RH is not known, one hypothesis suggests it may be due to vitreoretinal traction that occurs during repetitive acceleration-deceleration with or without blunt head impact. Other theories explore the possibility of increased intravascular pressure as the culprit behind vascular wall damage and hemorrhage, seen in Valsalva maneuvers or chest injuries. The exact reason for the extensive nature of RH involving the macula, periphery, and all layers of the retina is still not fully understood.

Computer simulations employing Finite Element (FE) analysis offer a valuable way to study AHT.This approach is relatively inexpensive compared to other models and has become popular due to its ability to incorporate both external and internal parameters that retainmaximum bio fidelity of the eyeball in response to predicted tissue stresses and strains. With the FE model, the eye is divided into very small pieces, akin to a brick (solid element) or thin plate (shell element), with similar physiologic properties and characteristics to an infant eye. These elements aggregate to produce an approximate model of an eye that can be manipulated computationally with relative conformity. Nodes can be created where the elements join to create flection points, and stresses may be applied to both the elements and nodes, to measure resulting forces.

Components of the infant eye, such as the unique hyper-viscous vitreous and firmly attached retina, can be incorporated into a FE eye model. Since 1999, a number of FE analysis models applicable to AHT or Shaken Baby Syndrome (SBS) have been developed to study the blunt impact following ocular trauma. However, previously created models assumed a homogenous, full-surface attachment between the retina and vitreous, ignoring stronger adhesive forces in particular structures including perivascular areas.

To better understand the mechanisms associated with AHT ocular manifestations, namely RH, we developed a new FE analysis of the eye and orbit that could be exposed to virtual forces experienced during shaking. A previous study on the physiologically biomimetic infant dummy doll via shaking by a human adult was used to define the parameters of acceleration, deceleration, range of motion of the eye in space, frequency of shaking, and velocity. This helped us to determine the compressive and tractional forces as well as the pressure applied to the retina and its vasculature using our FE model for the first time. Previous models only subjected the eye to simple rotational or translational movements along a single axis in an arc pattern. We examined our model by simulating multidirectional movements of the dummy doll model in a figure 8 pattern. Furthermore, we also examined the forces applied to different layers of the retina by dividing it into pre-retinal, intra-retinal and sub-retinal spaces using different elements for each layer. This allowed more precise forces to be applied to different sub layers of the retina and thus better understand the impact of the injury throughout the full thickness of the retina. This allows a correlation to the retinal hemorrhage patterns commonly seen in AHT related to violent shaking.

Results of our computer model show that shaking an eye at a frequency as low as 2.2 cycles per seconds can produce significant stress levels of 7 to 10 kPa along the retinal vessels. Coats et al studied the vitreoretinal adhesion in the equator and posterior pole in human eyes from donors ranging in age from 30 to 79 years old, and in sheep eyes from premature, neonatal, young lamb, and young adult sheep. They found that the retinal peel force in donor eyes from young adults 30 to 39 years of age (7.24 ± 4.13 mN) was similar to that of immature and young sheep eyes (7.60 ± 3.06 mN).Their results didn't include the exact area of force applied and so we were not able to convert to pressure units of kilopascal. If the area of the force applied to peel was 1 mm X 1 mm, the pressure would be approximately 7 kPa. Based on these results, mechanical failure of retinal tissue may occur in human infant eyes if stress levels exceed vitreoretinal adhesion.

With measured stress pressure values climbing to 10 kPa in the FE model at certain areas of vitreoretinal adhesions throughout the

***Corresponding author:** Donny W Suh, Truhlsen Eye Institute, University of Nebraska Medical Center, USA, Tel: 402-559-1867,402-955-8291; E-mail: dsuh@childrensomaha.org

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retina, this may exceed the vitreoretinal adhesion force. With multiple repetition of shaking and increased frequency, stress values may increase even further. Also, there may be some degree of tissue fatigue that may lower the force needed to result in mechanical failure of retinal tissue from vitreous, resulting in acute separation of these two structures at or near the vessels.

In conclusion, we developed a new FE analysis model that quantifies the distribution of forces at the vitreoretinal interface during shaking of AHT.Through this model, we advanced the understanding of the pathophysiological process of vitreoretinal traction leading to mechanical failure during forcible shaking of the eyes. If the force that is generated during shaking is greater than the force needed to maintain vitreoretinal adhesion, it may lead to retinal and vitreous separation acutely and breakdown of the blood vessel wall lining resulting in unique patterns of retinal hemorrhages. Ocular manifestations from AHT reveal unique retinal characteristics.Our FE model predicted stress patterns consistent with the diffuse retinal hemorrhages (RH) typically found in the posterior pole and around the peripheral retina in AHT. This model also showed that similar stress forces are produced in different layers of the retina at maximal speed, consistent with the finding that retinal hemorrhages are often found in multiple layers of the retina and the retinoschisis in AHT. Thus, our results suggest that diffuse RH involving the periphery near the vessel bifurcations associated with multilayer retinal involvement would besuggestive of significant force applied to the retina that may led to mechanical failure.

This information can be very useful for deciding whether to further pursue the extensive and careful medical and social history investigation of circumstances surrounding a trauma event.

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