Abstract Title: A Finite Element Analysis of the Fundus Hemorrhages Accompanied by Shaken Baby Syndrome / Abusive Head Trauma

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Introduction: Shaken baby syndrome or abusive head trauma (SBS / AHT) causes serious nervous damage including death to the infant victims. Fundus hemorrhage, bleeding within or around the retinal tissue, has been empirically recognized as a relatively specific marker of this syndrome, although the mechanism of which is not clearly understood. One hypothesis is that the vitreous, the transparent tissue filling a major volume inside the eyeball, pulls retinal tissue during the shake. Computer simulations are powerful tools to test this hypothesis because options in experimental approaches are limited. Some researchers have examined this hypothesis with a simulation method using elaborate finite-element (FE) mechanical models based on medical images. However, ironically, these models were too complex to make clear interpretation. We developed a FE mechanical model that is simple yet possessing essential features to analyze this phenomenon.

Methods: The eyeball model was generated by a Fortran95 program assuming a simple spherical geometry. The model consisted of the orbit, the fatty tissue, the sclera, the cornea, and the vitreous. HyperWorks v10.0 (Altair Engineering Inc.) was used as the integrated computer-aided engineering simulation software platform for the FE analysis. The orbit, the sclera and the cornea were modeled with quadrangular SHELL elements, which are planar elements defined by four nodes. The fatty tissue and the vitreous were modeled with hexahedral BRICK elements, which are steric elements defined with eight nodes. The spherical shape of the model contained no tetrahedral and pentahedral elements but only hexahedral elements, and contained a cubic portion in the center to avoid any singular nodes. The Young's moduli and the dimensions of each part were cited from literatures. One merit of this FE model is that its precision can be easily adjusted, which was made possible because this model is automatically generated by a computer program from scratch, to save any superfluous calculation time. The model was shook along the sagittal axis with sinusoidal acceleration or experimentally measured acceleration input by volunteer shakers.

Results: The pressure within a BRICK element at the posterior pole of the vitreous was monitored. The results suggested that it is likely that the pressure change in this part can trigger vitreous traction leading to fundus hemorrhages. The maximal absolute value of the negative pressure change reached 1 kPa, which is comparable to an experimentally determined threshold for retinal detachment of rabbit eyes described in a literature. The Young's modulus of the vitreous was rather arbitrarily set in our FE mechanical model because its precise measurement is difficult. Since the vitreous is known to gradually liquefy from the newborn gelled state along aging, the upper limit was set at 80 kPa, based on experience in pediatric ophthalmologist surgery. The lower limit was set at 1 kPa, where the simulation reliability relatively narrowly holds. The model with stiffer, or with higher value of Young's modulus in other words, vitreous exhibited larger pressure change, suggesting the stiffness of the vitreous of infants may make their fundus hemorrhages severer.

Conclusions: A simple and flexible FE mechanical model for analyses of the fundus hemorrhage accompanied by SBS / AHT was developed, which allowed clear analysis of the phenomenon. The simulation study suggested that the vitreous traction may cause fundus hemorrhage, and that the stiffness of the vitreous of infants' eyes may enhance the severeness of the injury.