PERIPAPILLARY DEFORMATION AND ITS RELATION TO MATERIAL PROPERTIES OF THE EYE GLOBE

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INTRODUCTION

Idiopathic intracranial hypertension (IIH), which is related to pseudotumour cerebri (PTC), is a state of increased intracranial pressure (ICP) with unknown cause. Common symptoms of IIH are headache, pulsatile tinnitus, nausea, transitory visual obscurations, diplopia and blurred vision. Signs of intracranial hypertension (IH) on magnetic resonance (MR) images of the eye include flattening of the posterior globe and inward protrusion of the optic nerve head. Optic nerve head protrusion, i.e. peripapillary deformation (PD), is mostly due to papilledema, which reflects swelling of the retinal ganglion cells that form the optic nerve due to axoplasmic stasis. However, there may also be a mechanical component related to the inverted 'U' shape that peripapillary Bruch's membrane takes in states of high ICP [1]. In this work, we performed a finite element (FE) analysis to investigate the important parameters that affect the mechanical response of the posterior globe. Furthermore, we used the FE model in order to determine mechanical properties of ocular tissues as well as IOP and ICP pressures, which might facilitate the observed nerve protrusion in patients with idiopathic intracranial hypertension.

METHODS

The geometry of the posterior globe and intra-orbital optic nerve, Figure 1, was created from the available information in the literature - 2-4]. The ANSYS APDL was used for conducting the finite element (FE) analysis. In the FE model, nodes on the axis of symmetry were constrained to deform such that they remain on the symmetry axis. In addition, because of anterior–posterior restraint of the extraocular muscles, nodes on the equator were constrained to radial deformation. Finally, since the degree to which the optic nerve is constrained is not fully known, a spring with normalized spring constant k was defined at the posterior ends of the dura mater and optic nerve, Figure 1.

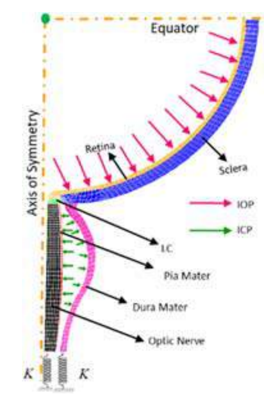

Figure 1: A schematic showing the computational model of the posterior globe. The model is radially symmetric and linear springs are used for end boundary conditions.

In order to assign the material parameters of the numerical model, a mid-axial MR image at the level of the optic nerve head was identified and measures of posterior eye NP (measured at the posterior scleral boundary) were obtained. The selection of a patient with high resolution MR imaging was done retrospectively based on the review of patients seen in the neuro-ophthalmology division at Byers Eye Institute at Stanford. This work followed the tenets of the Declaration of Helsinki and is approved by an institutional review board at Stanford University with a waiver of informed consent.

In order to relate the results of the MR image and the FE simulation, we used the angle-distance analysis technique [5] for characterizing the amount of PD. In this method, the actual boundary of the optic nerve head was considered in the MR image (shown by green color in Figure 2) and the displacement of peripheral nodes on the

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inner retinal surface from the center of the eye globe was plotted versus the angle θ. The same analysis was done for the finite element model, in which the model parameters were changed until the results matched those obtained from the MR image.

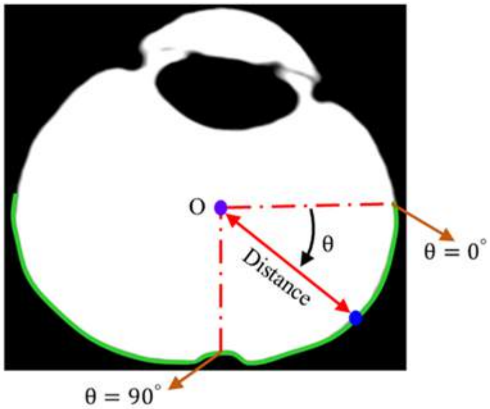

Figure 2: An MR image from a patient with high intracranial pressure. The outer boundary of the MR image is determined and was used for the angle-distance analysis.

RESULTS

Figure 3 shows the angle-distance graph obtained from the FE model matched very well with the curve obtained for a typical MR image shown in Figure 2. The numerical model showed that the amount of IOP and ICP and the material properties of lamina cribrosa, optic nerve, retina and pia mater were the most important parameters causing PD, i.e. the values of these parameters were significantly different than their default values. Furthermore, it was found that the end boundary conditions, modelled by linear springs, significantly influenced the amount of peripapillary deformation, Figure 4.

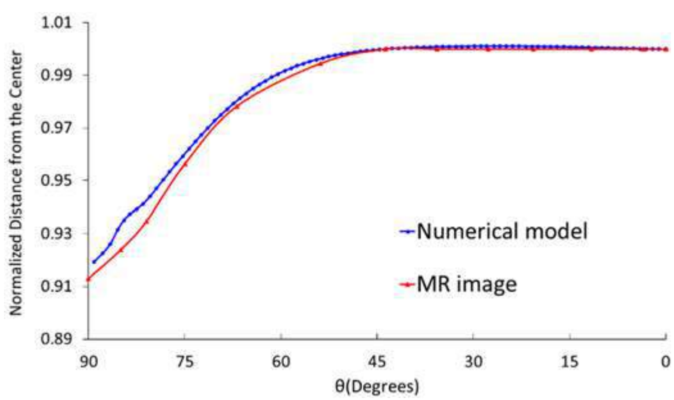

Figure 3: The Angle-Distance analysis of the finite element simulation of the MR image shown in Figure 2. The finite element results are obtained with IOP = 30 mm-Hg, and ICO = 70 mm-Hg. Furthermore, the modulus of pia mater, lamina cribrosa, optic nerve, and retina was 250, 25, 5, and 10 KPa, respectively.

DISCUSSION

Numerical models allow the isolation of mechanical from biological processes as well as enable researchers to manipulate parameters and measure outputs that cannot be accessed experimentally. Through manipulation of material properties, very good agreement was achieved between the numerical results and the MR image analysis of a patient with IH. These results supported the strength and suitability of developed characterization angle-distance technique for quantitative characterization of the contributing factors to the PD. Furthermore, it suggested that the proposed numerical model can be used in future studies to analyze MR images of patients with IH in order to estimate the average changes in the mechanical properties of tissues surrounding the ONH. Though it has been proposed that biological changes in the optic nerve head contributes significantly to nerve protrusion seen on MR images, the present numerical analysis suggests that there may exist a mechanical contribution as well. In other words, material properties as well as increased pressure loads could play a critical role in susceptibility to PD. This could occur due to either an individual's congenital variation in material properties of ocular tissues or acquired variation caused by tissue remodeling. The boundary conditions used at the bottom of the optic nerve and the dura mater were found important to the mechanical response of the globe.

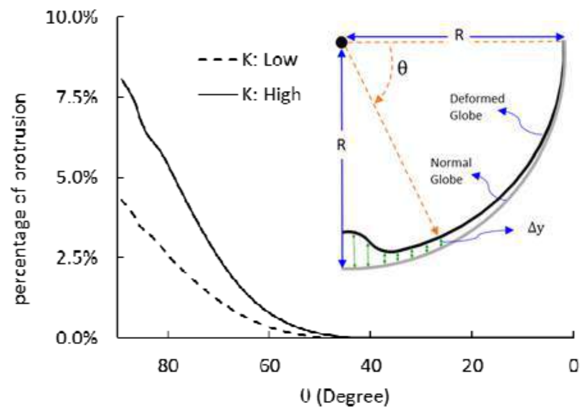

Figure 4: The effect of end boundary conditions on the amount of PD. The fixed boundary condition is obtained when the value of the spring constant is high. Except the spring constant, all other model parameters were the same as those used in Figure 3. Percentage of protrusion is $\frac{\Delta y}{R} \times 100$.

ACKNOWLEGMENTS

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