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THE EFFECT OF NONLINEAR SCLERAL PROPERTIES ON OPTIC NERVE HEAD BIOMECHANICS

Armin Eilaghi (1,2), Ian A. Sigal (1,2), Christian G. Olesen (1), Inka Tertinegg (3), John G. Flanagan (3,4), G. Wayne Brodland (5), C. Ross Ethier (1,2,4)

(1) Department of Mechanical and Industrial Engineering
University of Toronto
Toronto, ON, Canada

(2) Institute of Biomaterials and Biomedical Engineering
University of Toronto
Toronto, ON, Canada

(3) Department of Ophthalmology and Vision Sciences
University of Toronto
Toronto, ON, Canada

(4) School of Optometry
University of Waterloo
Waterloo, ON, Canada

(5) Department of Civil and Environmental Engineering
University of Waterloo
Waterloo, ON, Canada

INTRODUCTION

Glaucoma is a group of potentially blinding ocular diseases caused by gradual and progressive damage to the optic nerve, and is usually associated with elevated intraocular pressure (IOP) [1]. This damage occurs at the optic nerve head (ONH), the site where the optic nerve axons leave the posterior eye. IOP-related biomechanical factors are hypothesized to play a key role in the pathogenesis of glaucomatous damage [2].

A sensitivity study using the finite element method [3] showed that ONH biomechanics are strongly influenced by scleral stiffness and thickness. This fact highlights the importance of characterizing scleral properties for understanding the biomechanics of the ONH.

To our knowledge, all previous finite element models of ONH biomechanics have used linear material properties for the relevant tissues. Here we use a more realistic (nonlinear) stress-strain relationship for sclera in a generic finite element model of a human eye to compute the biomechanical environment in the ONH.

METHODS

Scleral samples of dimensions 6 mm x 6 mm were dissected from the scleral shells of a 65 year old male donor and tested as described in a companion abstract [4]. The measured stress-strain behavior of the sclera (the solid line in Figure 1) was implemented as a multilinear material model into a generic model of a human eye, including the optic nerve head (see figure 2 for detailed geometry [3] and terminology) and analyzed using a commercial finite element package (ANSYS 7.1, ANSYS Inc., Canonsburg, PA, USA). A uniform IOP of 25 mmHg was applied to all interior surfaces of the eye and the resultant first and third principal strains in ONH tissues were computed and compared to the outcomes of a previously published study [3] using linear scleral material properties (the dashed line in Figure 1). We focused on strains since it is believed that the cells in the ONH region respond to strain. For each tissue region and for each strain measure, the average strain and the 95th percentile of nodal strain values were calculated as a measure of mean and peak strains.

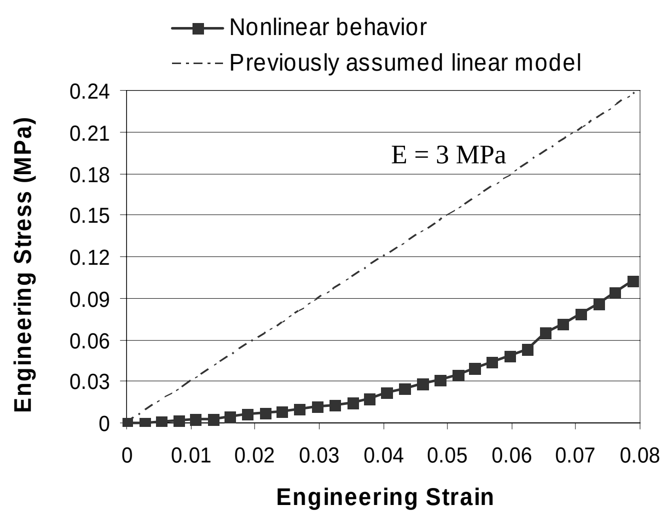

Figure 1. Solid line: The stress-strain behavior of a scleral sample taken from the scleral shell 9 mm inferior to the centre of the optic nerve and stretched uniaxially in the nasal-temporal direction Dashed line: Previously assumed linear elastic modulus for sclera, based on literature reports (E=3 MPa).

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RESULTS AND DISCUSSION

Levels of strain were significantly higher in all regions when using nonlinear scleral mechanical properties as compared to calculations based on linearly elastic scleral properties (Figure 3). Among the five tissue regions in the ONH, the sclera showed the highest increase in the mean strain values (250% and 340% for first and third principal strains). This significant proportional increase can be understood in view of the low tangent modulus of sclera that we measured at lower and physiologically meaningful strains. This is in contrast to single values reported for the modulus of sclera, which are often derived from tests at large, non-physiologic strain levels [5].

Consistent with a previous study [3], tissues experienced higher compression than extension in all regions. Of the ONH tissues, the magnitudes of both compressive and extensional strains were largest in the lamina cribrosa and the prelaminar neural tissue, followed by the sclera and retrolaminar neural tissue. The pia mater showed the minimum strain magnitude (Figure 3). In contrast to a previous study, the prelaminar region experienced higher strain than the retrolaminar region, which can be explained by there being less support from the more compliant sclera. In addition, the lamina cribrosa showed the most homogenous strain and the minimum difference between the peak (top 5%) and the mean values of strain.

Considering the peak strains, the retrolaminar, lamina cribrosa and prelaminar regions showed the highest first and third principal strains respectively (reaching ~15%), which were almost 3 times bigger than sclera and pia mater.

These results demonstrate the importance of nonlinear scleral mechanical properties on the biomechanical environment in the optic nerve head, and suggest that such properties could play a role in the risk of developing glaucomatous optic neuropathy.

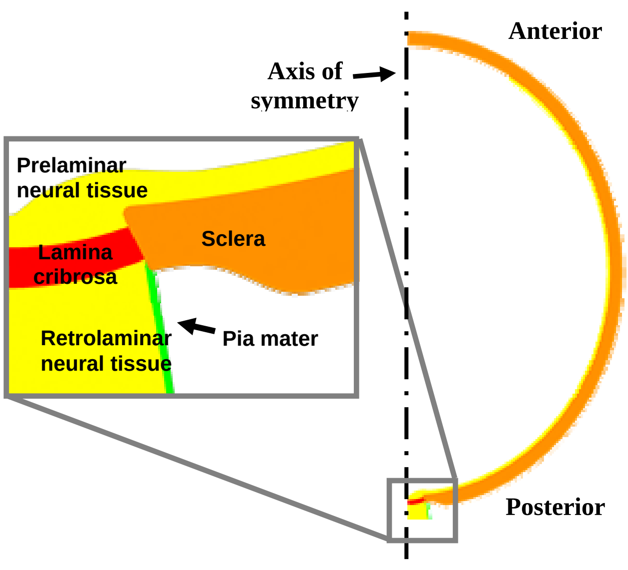

Figure 2. Finite element model geometry used in this research, based on [3]. The model had axial symmetry. The scleral shell is shown in orange, with a magnified view of the ONH region shown as an inset.

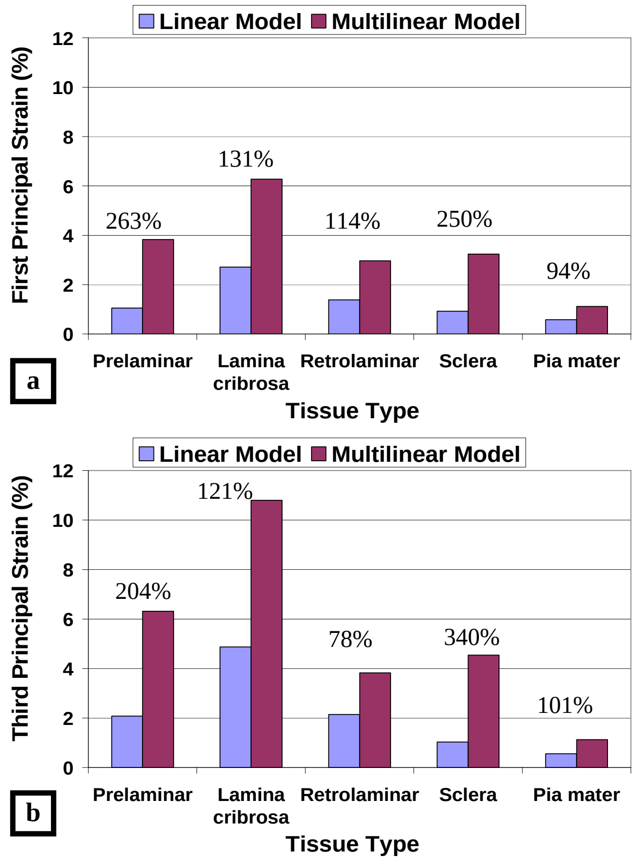

Figure 3. The average magnitudes of the a) first and b) third principal strains within each tissue of the ONH for linear and multilinear (nonlinear) scleral material properties. The percentage increase in the strain as computed by the multilinear model vs. the linear model is shown above each set of bars.

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