Proceedings of BioMed2008
3rd Frontiers in Biomedical Devices Conference
June 18-20, 2008, Irvine, California, USA

BIOMED2008-38051

COMPUTATIONAL MECHANICS OF THE SCLERA AND OPTIC NERVE HEAD (ONH): EFFECTS OF ONH SIZE AND PRESSURE RANGE

Lewis Waldman[1], *Insilicomed, Inc.* Crystal Cunanan[2], *Cascade Ophthalmics, Inc.*

Sanjay Asrani, *Duke University* Roy Kerckhoffs, *UCSD* Andrew McCulloch, *UCSD*

ABSTRACT

Computational modeling was performed to study how loss of compliance of the eye and abnormally high pressures result in changes in stresses and strains that may impact the optic nerve in diseases such as glaucoma. Hemispherical finite element models of the eye were created in which scleral thickness varied from the equatorial region to the optic nerve head (ONH). Nonhomogeneous material properties were used to model the ONH as a continuous region softer than the adjacent sclera. The ONH and an adjacent buffer zone in the sclera were modeled with enough detail that the size of the ONH could be changed to account for variations observed in humans. The model was provided with appropriate dimensions typical of patients and nonlinear material properties with decreased compliance. Models with different ONH sizes were inflated in small steps to 55 mmHg (7.33 kPa), providing deformed configurations at intermediate pressures of 15, 30 and 45 mmHg, respectively.

Color-coded maps of stress and strain components were rendered directly on deformed configurations of the eye model; and animations were produced that show both spatial and temporal variations of stresses and strains as internal pressure increases. Three-dimensional stresses and accompanying finite strains were similar for ONH sizes ranging form 1.5 to 2.5 mm in diameter. Stress and strain differences were estimated as pressure was increased from 15 to 25 mmHg, 30 to 40 mmHg, and 45 to 55 mmHg. Substantial changes occurred in stress and strain differences as the pressure range was varied with large changes occurring in the lowest pressure range for strain components and moderate increases in stress differences as pressures increase.

INTRODUCTION

High internal eye pressures associated with diseases such as glaucoma may contribute to elevated stresses in the sclera and increased deformation of the ONH. These mechanical factors may result in optic nerve damage emphasizing the need for detailed experimental studies correlated with realistic computational analysis under pathophysiologic conditions [1], [2]. Nonlinear mechanics was used to study the effects of ONH size and pressure range on strain and stress distributions in idealized geometries of the human sclera and ONH.

METHODS

Three-dimensional nonlinear, nonhomogeneous finite element models of the eye were created. To study the effects of elevated internal pressures on strains and stresses in the ONH and adjacent sclera, the eye wall was modeled as a hemisphere with wall thickness varying from 0.6 mm equatorially to 1.0 mm at the posterior pole and an internal radius of 10 mm in the undeformed state. The sclera was given nonlinear isotropic material properties that yielded stress-strain relations similar to those found in experimental studies of abnormally stiff eyes ([3], [4] and [5]. The ONH was given properties that were ten times more compliant than the adjacent sclera. Three models were created with ONH diameters of 1.5, 2.0 and 2.5 mm, respectively, and inflated in small steps to 55 mmHg. Finite strains in the ONH and Cauchy stresses in the adjacent sclera were estimated as pressure was varied. Differences in maximum and minimum principal strains in the ONH and maximum principal stresses in the sclera were estimated in low, mid and high pressure ranges.

RESULTS AND DISCUSSION

Color-coded maximum principal strains in the posterior region of the eye model at an internal pressure of 55 mmHg were rendered in a cross-sectional view (Fig. 1a). Strains are large throughout the optic nerve region which bulges to the posterior with peak principal stretches greater than 1.15 (15%). Estimates of maximum and minimum principal strains in the soft region increase nonlinearly to large magnitudes with increasing internal eye pressure (Fig. 1b) and are similar for varying ONH sizes with small increases in strain distributions throughout the largest ONH region. Color-coded maximum principal stresses in the posterior region at the maximum pressure were also rendered (Fig. 2a). Large stress concentrations are confined to narrow regions adjacent to the ONH where scleral stresses increase linearly with pressure to large values (Fig. 2b) and are similar for varying ONH sizes with peak values greater than 80 kPa.

Estimates of maximum and minimum principal strains in the ONH and maximum principal stresses in the adjacent sclera in three pressure ranges are given in Table 1. Differences are given as pressure is increased by 10 mmHg from each baseline pressure. Peak strains

[1] Contact Information: Lewis Waldman, Insilicomed, Inc., 427 Vincente Way, La Jolla, CA 92037, waldman@insilicomed.com or

[2] Crystal Cunanan, Cascade Ophthalmics, Inc., 18 Technology Dr., Suite 147, Irvine CA 92618, ccunanan@cascadeoptx.com

increase by large amounts in the low pressure range; increases are greatly reduced in the highest range. Peak stress differences increase moderately with pressure range with the greatest increase occurring in the highest range reflecting the nonlinear properties.

Stress concentrations estimated in the posterior sclera and large strains in the adjacent ONH at elevated internal pressures may contribute to conditions that lead to optic nerve damage. Assumptions in this analysis include isotropic, elastic properties in both regions of the eye wall and axisymmetry. Further modeling should be performed with relaxed assumptions and more detailed correlation with experiments.

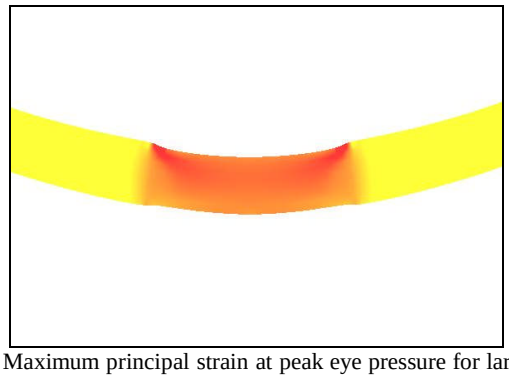

Fig. 1a: Maximum principal strain at peak eye pressure for large ONH (2.5 mm diameter); note: large strains in ONH region (red: maximum finite strain: +0.164; stretch: 1.152).

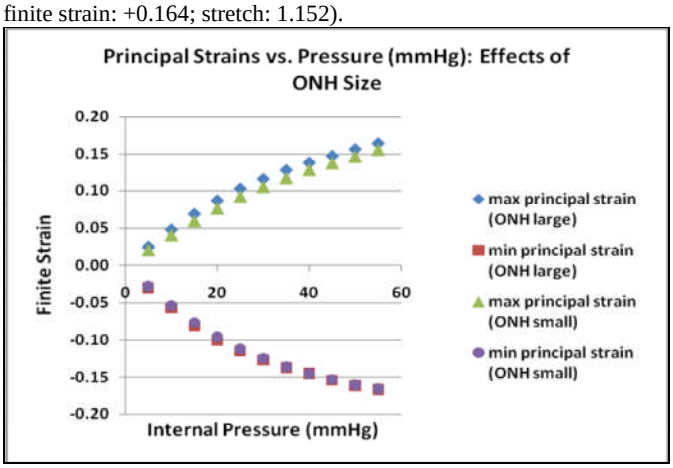

Fig. 1b: Maximum and minimum principal strains vs. eye pressure for small (1.5 mm diameter) and large ONHs (2.5 mm diameter).

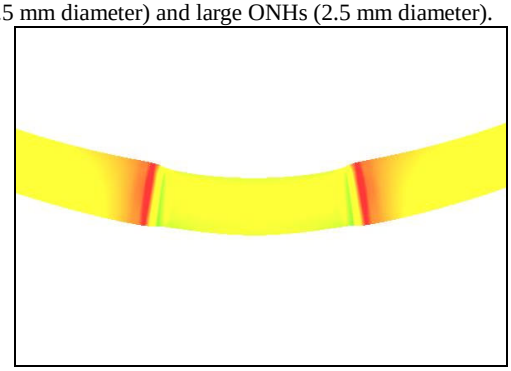

Fig. 2a: Maximum principal stress at peak eye pressure for large ONH (2.5 mm diameter); note: large stress concentrations in sclera adjacent to ONH; (red: maximum Cauchy stress: +80.65 kPa).

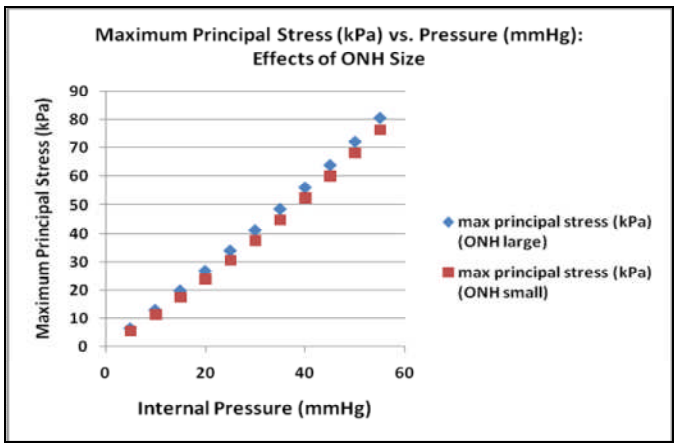

Fig. 2b: Maximum principal stress vs. internal eye pressure for small (1.5 mm diameter) and large ONHs (2.5 mm diameter).

Table 1: Estimated Principal Strains and Stresses (kPa) at Low, Mid and High Baseline Pressures and Differences with ΔP = +10 mmHg for Large (2.5 mm OD) and Small ONH Sizes (1.5 mm)

Press.	Mean	Diff.	Mean	Diff.	Mean	Diff.
mmHg	15	15 to 25	30	30 to 40	45	45 to 55
E_3^{max} (lrg)	0.069	*+0.034*	0.116	*+0.022*	0.147	*+0.017*
E_3^{max} (sml)	0.059	*+0.033*	0.105	*+0.023*	0.137	*+0.018*
E_1^{min} (lrg)	-0.081	*-0.034*	-0.127	*-0.018*	-0.154	*-0.013*
E_1^{min} (sml)	-0.077	*-0.035*	-0.125	*-0.020*	-0.153	*-0.013*
T_3^{max} (lrg)	19.79	*+14.15*	41.20	*+14.78*	63.90	*+16.75*
T_3^{max} (sml)	17.37	*+13.16*	37.54	*+14.77*	60.11	*+16.30*

E_3^{max}:maximum value of third principal strain throughout ONH;
E_1^{min}: minimum value of first principal strain throughout ONH;
T_3^{max}:maximum value (kPa) of third principal stress in adjacent sclera.

ACKNOWLEDGMENTS

The Continuity software licensed exclusively by Insilicomed, Inc. from the University of California was used in this analysis (Copyright © 2007 by University of California).

REFERENCES

[1] Burgoyne CF, Downs JC, Bellezza, AJ, Suh JKF, Hart RT. The Optic Nerve Head as a Biomechanical Structure: A New Paradigm for Understanding the Role of IOP-related Stress and Strain in the Pathophysiology of Glaucomatous Optic Nerve Head Damage. *Prog Ret and Eye Res* 24:39-73, 2005.

[2] Sigal, IA, Flanagan JG, Tertinegg I, Ethier CR. Predicted Extension, Compression and Shearing of Optic Nerve Head Tissues. *Exp Eye Res* 85(3):312-322, 2007.

[3] Anderson K, El-Sheikh A, Newson T. Application of Structural Analysis to the Mechanical Behaviour of the Cornea. *J R Soc Interface* 1:3-15, 2004.

[4] El-Sheikh A, Wang D, Kotecha A, Brown M, Garway-Heath D Evaluation of Goldmann Applanation Tonometry Using a Nonlinear Finite element Ocular Model. *Annals of Biomedical Engineering* 34(10):1628-1640, 2006.

[5] Pallikaris IG, Kymionis GD, Ginis HS, Kounis GA, Tsilimbaris MK. Ocular Rigidity in Living Human Eyes. *Invest Opthalmo Vis Sci.* 46(2):409-414, 2005.