Proper Material Properties Are Required for the Finite Element Method

The finite element method is now widely used in all areas of medicine and dentistry. We are pleased to see that Stitzel et al[1] used the finite element method to analyze the effects of blunt trauma to the eye. Stitzel and colleagues found that lens stiffness is a critical parameter in the eye's response to blunt injury. However, the proper choice of baseline material properties is essential for the finite element method to reliably predict this or any other outcome.

We are concerned with the accuracy of the baseline data used by Stitzel and colleagues in determining the lenticular elastic modulus. The elastic modulus is a measure of stiffness that is calculated as shown in the following formula:

$$\begin{array}{c}\text{Elastic}\\ \text{Modulus}\end{array} = \frac{\text{Stress}}{\text{Strain}} = \frac{\begin{array}{c}\text{Force per}\\ \text{Unit Area}\end{array}}{\begin{array}{c}\text{Change}\\ \text{in Length}\\ \text{per}\\ \text{Baseline}\\ \text{Length}\end{array}} = \begin{array}{c}\text{Newtons}\\ \text{per Square}\\ \text{Millimeter}\end{array} = \text{Megapascals}$$

Stitzel and colleagues obtained an elastic modulus of 6.89 MPa for the group of patients aged 66 years or older from force displacement measurements of cataractous lens nuclei in vitro.[2,3] We are unable to determine how they calculated the force per unit area required for the elastic modulus from force per unit displacement data. The magnitude of this lenticular elastic modulus appears to be exceedingly high, for it makes the lenticular modulus 5 times stiffer than that of the cornea (1.24 MPa as assigned by Stitzel and colleagues) and twice that of the sclera (3.58 MPa as assigned by Stitzel and colleagues).

Stitzel and colleagues assumed that there was a linear relationship between the elastic modulus and age. Using 6.89 MPa for the elastic modulus of the group of patients aged 66 years and older, they proportionally assigned lenticular elastic moduli to the younger groups based on deformation measurements of spinning human lenses made by Fisher[4] in 1971.

We challenge the accuracy of the measurements made by Fisher and, therefore, the choice of the data in the analysis by Stitzel and colleagues. For example, from the data by Fisher,[4] the cortical stiffness of a lens of a 29-year-old patient is 6 times that of its nucleus (see Table 4 in the article by Burd et al[5]). Brillouin light scattering,[6] dynamometric measurements of fresh human lenses in vitro,[7] and clinical observation of nuclear hardness during phacoemulsification in vivo all demonstrate that the nucleus of lenses in patients older than 25 years is either of the same or of much greater hardness than that of the cortex.[8]

The speed of sound in the lens, which is directly dependent on the lenticular elastic modulus,[9] has been found to be constant in subjects between ages 15 and 45 years.[10] Therefore, the elastic modulus would not be expected to change in the lenses of eyes from patients younger than 45 years. Even though the elastic modulus of thawed lenses following freezing in liquid nitrogen[11,12] appears to be significantly higher than that of fresh lenses, these measurements do not demonstrate any significant change in the elastic modulus of lenses in younger patients.[11-13] Furthermore, the optical density of lenses in vivo[14] of patients younger than 39 years is constant. These observations all suggest that the choice by Stitzel and colleagues of baseline material properties of the lens and their assumption that lens stiffness is linearly related to age are inappropriate.

In addition, Stitzel and colleagues assigned extremely high elastic moduli of 358 MPa and 11.00 MPa for the zonules and the ciliary body, respectively. The reported elastic moduli for the zonules and ciliary muscle are 1.5 MPa and 0.12 MPa, respectively.[15] It would be very interesting to see whether the observations and conclusions by Stitzel and colleagues would be altered if they were to use these different values for the elastic moduli.

We greatly appreciate their contribution to the method of analyzing the effects of blunt trauma and look forward to the continued application of the finite element method to the eye.

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In reply

We thank Drs Schachar and Abolmaali for their insightful comments. We are in agreement that the finite element method is an excellent way to analyze the effects of blunt trauma to the eye.

The elastic modulus of the lens was obtained from the results by Fisher.[1,2] A simplification of that data using graphical force displacement with an assumption of the average cross-sectional area for an oblong sphere (lens shape) and standard force displacement measurements for an oblong sphere assuming linear elastic behavior was used to determine the elastic modulus through inverse dynamics.

We could not directly use the previously published lens stiffness data by Czygan and Hartung[3] because of a difference in method. The lens modulus may not warrant direct comparison to the cornea or scleral moduli, as the cornea and scleral "elastic" moduli are not linearly elastic. The material properties are nonlinear in their stress-strain behavior. Elastic moduli are given as an approximation to the first portion of the curve originally obtained by Yamada[4] and implemented by Stitzel et al.[5] The modulus of the lens has been reported to be as low as 2 kPa, or 0.002 MPa, by Weeber et al[6] (see the interpretation by Fisher[1,2] and van Alphen and Graebel[7]). The data by Czygan and Hartung[3] using an interpretation of data used by Weeber and Eckert,[8] about 0.2 mm of compression at 0.8 N of force assuming a 2-mm-thick sample with a 4-mm diameter to represent lens nuclei, gives a stiffness of 0.636 MPa, or 318 times the stiffness given by the interpretation of the data found by Fisher[1,2] and van Alphen and Graebel[7] that was made by Weeber et al.[6,8] Our own assumption for an elderly individual gives an elastic modulus that is 10.8 times higher than this example, or much closer than 318 times the stiffness. Methods used to assess lens moduli are in need of standardization. Unfortunately, in interpreting the eye biomechanics literature, a lack of standardization makes it possible to refute any testing.

We did not assume a linear relationship between elastic modulus and age; we proportionally assigned lenticular elastic moduli to the younger groups based on stiffness data obtained by Fisher.[1,2] We assumed that the relationship was the same for our moduli as it was for the moduli by Fisher.

We did not independently consider the stiffness of the nucleus vs the cortex of the lens in our model. The stiffness of the lens nucleus is generally higher than that of the cortex, a fact confirmed by Weeber and Eckert.[8] However, the relationship is more complex. We did not use data by Fisher[1,2] in our analysis; instead, we used an interpretation by Czygan and Hartung[3] and scaled based on the data by Fisher and an assumption that the Young modulus of elasticity and the Young equatorial modulus of elasticity follow the same trend with age. In lenses of patients younger than 30 years, the nucleus is softer than the cortex; in lenses of patients older than 30 years, the nucleus is harder than the cortex.[9] Changes in nuclear stiffness greatly exceed those in the cortex, dominating overall response, which supports our use of Fisher testing of nuclei to describe overall lens stiffness.

We cannot agree with the assertion that the lens does not change stiffness in patients younger than 45 years. The speed of sound is a product of elasticity and density, and it should not be used without caution as a direct indicator of the change in elastic modulus. The change in lens stiffness with age is well documented. Weeber et al[6,8] discuss the change from ages 18 to 90 years. Data by Fisher[1,2] demonstrate a slight change from ages 20 to 30 years and a much-increased slope from ages 30 to 40 years. Articles[6,9] cited by Drs Schachar and Abolmaali to refute lens stiffness changes in patients younger than 45 years both state that a change in the elastic modulus was found with age, even in the young age range. The stiffness values varied almost 1000-fold over the age range of 14 to 78 years.[9] The largest change was observed from ages 20 to 60 years. Although presbyopia is qualitatively associated with an onset later than age 50 years, the change in accommodative power of the lens with age is clearly documented as early as age 14 years.[10-13] Weeber et al[6] state interesting, salient points but do not give peer-reviewed data refuting a change in stiffness in patients younger than 45 years.

The zonules are stiffer than the lens when taken in tension, and the zonules are unable to resist bending stresses or shear stresses. The muscular ciliary body has little resistance to bending but resists tension. Our parameter assumptions are like those made by van Alphen and Graebel.[7] Values of 1.5 MPa and 0.12 MPa for the zonules and ciliary body, respectively, deserve consideration in a dynamic model of the eye.[7] It would be interesting to see how incorporating these properties would change our results. It would be very informative to change the values put into a finite element model by orders of magnitude to determine the effect on model response. Our main goal was to incorporate the relative difference in stiffness between components—we assigned the modulus of zonules to be 10 times stiffer than the sclera in our model given what we know about the stiffness of an individual zonule. We assigned 11.00 MPa to the ciliary body based on values reported previously for muscle tissue in the literature, albeit in compression. The values given by van Alphen and Graebel[7] are in an appendix to the article, put forth "as provisional Young's moduli at 10% elongation, to allow comparison with Fisher's figures,"[7] and van Alphen and Graebel go on to say, "We present these figures with all proper reserve since they include assumptions of homogeneity, isotropy, and linearity, and neglect complications of transverse effects in nonlinear elastic tissues."[7]

We should add a positive comment. The eye model is sophisticated and is the first to take into account the interaction of fluids and solids in a dynamic impact to the eye. That is a key difference between the model that we have created and many models available in the literature.

Thank you very much for your comments. We also look forward to the continued application of finite element modeling to understand the mechanics of the eye.

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