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Sensitivity study of human crystalline lens accommodation

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ABSTRACT

A nonlinear axisymmetric finite element method (FEM) analysis was employed to determine the critical geometric and material properties that affect human accommodation. In this model, commencing at zero, zonular traction on all lens profiles resulted in central lenticular surface steepening and peripheral surface flattening, with a simultaneous increase in central lens thickness and central optical power. An age-related decline in maximum zonular tension appears to be the most likely etiology for the decrease in accommodative amplitude with age.

1. Introduction

The young human eye can rapidly change optical power by altering the shape of its crystalline lens. The induced change in focal length is called accommodation and is measured in diopters; i.e., the inverse of the focal length in meters.

The crystalline lens is axisymmetric with a mid-sagittal profile similar to an ellipse with minor (central thickness) and major diameters (equatorial diameter) of approximately 4 and 9 mm, respectively. The lens consists of 35% protein and 65% water. It is totally transparent and enclosed in a thin membrane capsule. The lens is located behind the iris approximately 3 mm from the apex of the cornea with its axis of symmetry approximately coincident with the optical axis of the eye. It is suspended in the eye between the aqueous humor and the vitreous body by zonular fibers that are inserted into the equatorial region of the lens capsule. The zonular fibers originate in the ciliary body and transduce the force of contraction of the ciliary muscle to the lens capsule. Contraction of the ciliary muscle induces lenticular accommodation.

The mechanisms of lenticular accommodation and its age-related loss continue to be of great interest [1]. The amplitude of human accommodation declines at the approximate rate of 0.25 diopters/year. By the mid-forties, the near point of vision is more distant than that required for reading. When this occurs, the patient has demonstrated presbyopia [2,3]. By the age of 50, little residual ability to change focus remains.

Unfortunately, direct, *in vivo*, measurement of most of the geometric and material properties of the whole human lens is not possible. Alternative approaches are, therefore, needed to characterize and understand the mechanism of lenticular accommodation and its change with aging.

The finite element method (FEM) coupled with a sensitivity study is a reliable method for determining the critical physiological factors that affect biological tissues [4–6]. In a sensitivity study, the geometric and material properties are varied

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to determine the physiological limits of each variable within the constraints of the system [7–10]. The present study uses a sensitivity study to establish the physiologic range for the geometric and material properties of the lens and their effect on the mechanism of accommodation and its age-related decline.

Several analyses of human lenticular accommodation have been published using nonlinear FEM [11–15]. However, the present FEM analysis differs markedly from these prior studies in several important ways. This analysis is a sensitivity study, using quadrilateral elements to represent the capsule, surface-to-surface contact elements between the capsule and cortex, and satisfying all of the constraints on the force, topography and anatomy of human lenticular accommodation.

2. FEM model

2.1. Baseline geometric properties

It has not yet been possible to determine, *in vivo*, the human lens shape at high resolution. The available magnetic resonance images (MRI) of *in vivo* entire human lens profiles have resolutions that are less than 150 μm. This limitation in resolution makes current MRI images insufficient to delineate the exact radius of curvature of the lens surfaces.

In order to address this limitation, our model employs a function for the anterior and posterior surface of the baseline lens that best fits the available MRI profile of the whole lens. This function is continuous and has the following essential requirements:

1. The radii of curvatures at any point on the lens surface are smoothly varied.
2. The radii do not change abruptly near the optical axis.
3. The radii are identical at the equator where the anterior and posterior surfaces meet.
4. The functions have a positive Gaussian curvature everywhere on the surface.

This function is [16]:

$$y(x) = \left[b + c\left(\sin^{-1}\left(\frac{x}{a}\right)\right)^2 + d\left(\sin^{-1}\left(\frac{x}{a}\right)\right)^4\right] \times \cos\left(\sin^{-1}\left(\frac{x}{a}\right)\right) \tag{2.1}$$

The lens profiles, profiles I and II [17]; profile III [18] and profiles IV and V [19] were obtained from published MRI images. The coefficients employed in Eq. (2.1) for each lens profile are given in Table 1. The capsular thickness variation was incorporated in all profiles using the functions given by Chien et al. [16]. The thickness of the center of the anterior and posterior capsules, at baseline, was 24 and 5 μm, respectively [20,21]. The thickness of the nucleus of the lens model was calculated as a percentage of its central lens thickness (CLT), based on *in vivo* Scheimpflug measurements [22] (Fig. 1a, Table 1).

2.2. Baseline material properties

2.2.1. Lens stroma (cortex and nucleus)

The bulk modulus, K, of the human lens cortex and nucleus is 2.8 and 3.7 GPa, respectively [23], as measured by non-invasive Brillouin light scattering, These bulk moduli determined *in vitro*, are consistent with those calculated *in vivo*, using the speed of ultrasound in young human lenses [24], and the density of the lens [25].

Pieces of young adult human lenses (14–25 years of age), stored in liquid nitrogen, were used to determine the mean shear modulus, $G = 50$ Pa [26]. The Poisson's ratio, ν, and the elastic modulus are related to K and G by the following

Table 1 – Geometrical properties of the lenses

	Profile I	Profile II	Profile III	Profile IV	Profile V	Idealized
Coefficients for anterior profile Eq. (1) (mm)						
a	4.485	4.2815	4.5	4.5	4.3	4.3
b	1.2089032	1.463629	1.55467	1.439666869	1.75102	1.9
c	−0.266892	−0.166822	−0.329	−0.0962011	−0.130361	0.1795833
d	0.1166546	−0.021135	0.08141	0.11257732	0.117481	−0.3848683
Coefficients for posterior profile Eq. (1) (mm)						
a	4.485	4.2815	4.5	4.5	4.3	4.3
b	2.1669011	2.260218	2.27038	2.377780173	2.628273	2.00
c	−0.368996	−0.259828	−0.6326	−0.58929807	−0.964052	−0.192903226
d	0.0006791	−0.114285	0.0869	0.158321934	0.311269	−0.25033071
Dimensions for the lens outline (see Fig. 1b) (mm)						
a	4.485	4.2815	4.5	4.5	4.3	4.3
e	0.3570	0.3938	0.4045	0.4037	0.4631	0.4045
f	2.5565	2.4405	2.3850	2.7900	2.6660	2.8504
g	0.8768	1.0232	1.1352	0.9508	1.1285	0.9714
h	1.9242	2.1226	2.0273	2.3668	2.7152	2.4180
i	1.2089	1.4636	1.5547	1.4397	1.7510	1.900
j	2.1669	2.2602	2.2704	2.3778	2.6283	2.000
t	3.3758	3.7238	3.8250	3.8174	4.3793	3.900