Abstract

The structure of the human eye is almost spherical, elastic and the properties of the components are considerably age-related. The main parts of the eye are the sclera, the cornea, the ciliary muscle, the zonular fibers and the crystalline lens. We have built a complex three dimensional finite element model which contains the biologically and mechanically required parts for biomechanical analysis. We have examined the accommodation problem based on the classical Helmholtz theory according to the age-related changes in geometry and material. Based on mechanical and optical consideration, in this paper we would like to give answers why our accommodation width decreases with increasing age.

Introduction

The eye is one of the most important sensory organ of the human body. There are several studies and numerical investigations which dealt with this subject. The widespread fields of research in this topic are the following: accommodation of the human eye, reasons of presbyopia, effect of eye surgeries and so on. Many studies dealt with these parts separately ([1], [4], [11]) but the complex modeling of the human eye is rare, so we tried to develop a numerical model to analyse several problems. In this article we introduce our three dimensional finite element model and its application to examine the accommodation process.

Accommodation

First of all very shortly we have to discuss what the accommodation of the human eye is. To answer this question we have to look over the main parts of the eye. These parts are the sclera, the cornea, the ciliary muscle, the zonula fibers and the crystalline lens with nucleus, cortex and capsule (see Figure 1).

![Fig. 1. Section of the human eye and the accommodation process](www.micrographia.com; aglasser.opt.uh.edu)

The ciliary muscle contraction causes the lens to thicken and change shape. It allows us to see objects closely (see Figure 1). This is the accommodation process. When we are young our crystalline lenses are soft and flexible so they are able to change their shape easily, allowing focusing on objects both close and far away. Around the age of 40 our crystalline lens becomes less flexible (more rigid, higher Young's modulus) what makes it more difficult to see close. We call this presbyopia ("aging eye"). The accommodation width is the difference between the lens diopter when seeing near and the lens diopter when seeing far. The central optical power (COP) is the diopter of the lens in its axis. We calculated the optical power based on the conventional lens formula:

\[
COP = \frac{n_l - n_p}{r_a} + \frac{n_l - n_p}{r_p} - \frac{f(n_l - n_p)^2}{r_a r_p n_l}
\]

where \(n_l\) - which is the refractive index of the lens - is assumed to be around 1.44 but it is age-related (see Figure 2); \(n_p\) - which is the refractive index of the aqueous humour and the vitreous body - is assumed to be...
1.336; \( r_a \) and \( r_p \) is the anterior and posterior radii of curvature; \( t \) is the thickness of the lens. To determine the radii of curvature we used a polynomial regression on nodes in our 3D finite element model.

**Fig. 2.** Lens refractive index decreases with increasing age (Moffat et al.[12])

**Finite element model**

Our 3D complex continuum model contains the following anatomical parts of the eye: sclera, cornea, ciliary body, the lens with its three parts (lens nucleus, lens cortex, capsule), aqueous humour, vitreous body, zonular fibers and the supporting fat tissue (see Figure 3). For the finite element analysis we use ANSYS classic and ANSYS workbench software.

**Fig. 3.** Young’s modulus of cortex and nucleus with increasing age (Fisher [6])

The geometrical and material properties are quite age-related (see Figure 3). The applied geometrical and material properties based on several works: Fisher ([5],[6],[7]), Abolmaali et al. ([11]), Burd et al. ([4]), Krag et al. ([8], [9]), Levin et al. ([10]), Liu et al. ([11]), Power ([13]), Strenk et al. ([14]). The material models were linear elastic, isotropic.

**Fig. 4.** Fatty tissue, the supports and the section of our FE model
We used shell elements (SHELL281) for zonular fibers and lens capsule, and volume elements (SOLID186) for the rest (see Figure 4).

We applied an axisymmetric tension force on zonular fibers across the ciliary muscles ([3]). So we stretched the lens from the accommodated state to the unaccommodated state (see Figure 5). As a boundary condition we set zero displacements on those nodes which are lying on the supporting surface at the border of the fatty tissue (see Figure 4).

\[
\begin{align*}
\text{Fig. 5. The displacements in lens axis direction, section view and only the eyeball}
\end{align*}
\]

**Numerical results**

We would like to analyse the accommodation width with aging. The initial geometry and the intensity of the stretching force were the same, but the material properties of the lens nucleus, cortex and capsule, and the thickness of the capsule were diverse in the different ages (see Table 1). In Figure 6 we can see the displacements of the anterior and the posterior surface of capsule in lens axis. Figure 6 has also shown the changes in lens thickness with increasing age. Since the crystalline lens becomes less flexible (more rigid) the changes in lens thickness are increasing due to the complex model.

We calculated the central optical power (COP) of the lens with the initial geometry and with the deformed shape (in accommodated and unaccommodated states). If we neglect the fact that the refractive index of lens is not constant in every age we receive the results what we can see in Figure 7.

Because the initial geometry (accommodated state) was the same in each analysed age, and the refractive index was constant too we can see different optical power only in the unaccommodated states (as shown in Figure 7 left side). The decreasing tendency of accommodation width is based on numerical and optical calculations and is shown in Figure 7 right side.

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Age [yr]} & \text{Young's modulus of nucleus [MPa] } \nu=0.49 & \text{Young's modulus of cortex [MPa] } \nu=0.49 & \text{Young's modulus of capsule [MPa] } \nu=0.47 \\
\hline
20 & 0.000862 & 0.002766 & 1.00 \\
30 & 0.001329 & 0.003474 & 1.30 \\
40 & 0.002156 & 0.003886 & 1.45 \\
50 & 0.003433 & 0.004000 & 1.45 \\
60 & 0.005250 & 0.003818 & 1.45 \\
\hline
\end{array}
\]

*Table 1. The material properties of the crystalline lens*
Considering that the refractive index of the crystalline lens decreases with increasing age (see Figure 2) we calculated the optical power of the lens and the accommodation width with different refractive index in different ages (see Figure 8). We can say that the accommodation width is getting worse if we consider the decreasing of the refractive index of the lens.

**Conclusions**

Based on the finite element calculation our numerical results confirm that the accommodation width ($\Delta COP$) reduces with aging. Considering the age-related material properties we saw that the effect of the refractive index is also important. According to this the accommodation width is getting worse. If we compare our numerical results with measured results ([15]) based on defocusing technique we obtain the following diagram (Figure 9).
Subjects were divided into 3 age groups: younger than 30 years (Group 1), between 31 years and 44 years (Group 2), and older than 45 years (Group 3) ([15]).

With this information we established that not only the age-related material properties but the age-related optical properties are important with the same weight in the accommodation width changes.

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References


