·Basic Research·

A study on accommodation mechanism with numerical simulation

Zhuo Liu[1,2], *Bo-Liang Wang*[2], *Shi-Hui Wu*[3], *Xiu-Ying Xu*[2], *Pei-Shan Dai*[1], *Ying Ju*[2], *Jie-Zhen Xie*[2], *Xiao-Yang Huang*[2]

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[1]College of Electronic Science and Engineering, National University of Defense Technology, Changsha 410073, Hunan Province, China
[2]Department of Computer Science, Xiamen University, Xiamen 361005, Fujian Province, China; [3]Department of Ophthalmology, Hospital of Xiamen University, Xiamen 361005, Fujian Province, China

Correspondence to: Zhuo Liu. College of Electronic Science and Engineering, National University of Defense Technology, Changsha 410073, Hunan Province, China. ewliuzhuo@163.com

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Abstract

• AIM: To study accommodation mechanism with numerical simulation.

• METHODS: A simulation model was constructed to study the mechanism of accommodation based on the experimental data derived from published resources. The displacement and pressure were applied on the model to study the deformation of lens during accommodating.

• RESULTS: The simulation showed that, as the eye was accommodating, the thickness of the lens increased linearly, and the lens diameter decreased linearly. The optical power of the lens increased as the accommodation increased. This result was accord with the public facts in accommodation. Furthermore, the pressure was found to have a great influence on the shape of the lens and the optical power. The lens became thinner and flatter as the pressure increased and the pressure caused a remarkable increase of lens' optical power.

• CONCLUSION: The outcome of this paper is consistent with the Helmholtz's hypothesis on accommodation to some extent. The analytical model presented in this paper can be used in the theoretical study of the accommodation mechanism of the human lens.

• KEYWORDS: human crystalline lens; simulation; optical power; accommodation; eye pressure

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INTRODUCTION

The deformation of human crystalline lens has been considered as the physiological basis of vision accommodation, which is believed to be due to the contracting or relaxing of the ciliary muscles and the zonules. However, the mechanism of lens accommodation is still under discussion. One popular viewpoint was proposed by Helmholtz[1]. He believed that the optical power decreased as the ciliary muscles contracted and increased as relaxed. Although Helmholtz's hypothesis has been accepted widely, many studies threw doubt on this viewpoint. In 1992, Schachar [2] propounded a contrary viewpoint that the optical power increased as the ciliary muscles contracted. The most direct and accurate method to study the lens accommodation is to measure the accommodating lens *in vivo*, but the lens is normally partially obscured by the iris and direct measurements of changes in ciliary body and lens during the accommodation process are difficult. *In vitro* studies can provide the opportunity of making more detailed measurements and can obtain much richer data. However they are subject to the important uncertainty that the conditions of the lens and surrounding issues may not be equivalent to *in vivo* conditions.

Recently, theoretical analysis method based on the mathematical model of the lens has been used to study the mechanism of lens accommodation. Sophisticated mechanical analysis becomes available by using the computer-aided design and finite element analysis. Schachar and the coleagues [3] used a mathematical method to study the accommodating lens in order to prove Schachar's hypothesis of accommodation. Burd and the coleagues [4] constructed a finite element model of the lens and the zonules to study the mechanism of accommodation. Shung [5] examined the deformation effect of the lens when a few periodical radial points pulls were applied at the lens equator using his finite element model. Theoretical analysis provides great possibilities that are not available in experimental studies, which makes it to be a useful supplement to experimental studies of the accommodation mechanism.

The purpose of this paper is to construct a simulating model of the lens and the zonules, which is different from existing models in detailed modeling procedure and parameters, to study the deformation of accommodating lens.

MATERIALS AND METHODS

Geometric Model of the Human Crystalline Lens In this study and all previous ones, the lens was assumed to be axisymmetrical. Under this assumption, only the profile data were needed to construct a lens. The measurement and mathematical description of the lens profile were very important to model the lens, but it was beyond the scope of this paper. In this paper the published data by Fincham[6] and Brown [7] were used to describe the lens shape. Figure 1 shows the profile of the lens and zonules, with main parameters annotated.

The capsule thickness was known to vary with radial position instead of being even on the outer surface. We used the data measured by Fish and Pettet [8]. The thickness curve of the lens capsule is shown in Figure 2.

Material Properties of the Lens and Zonules The lens model consisted of three distinct materials: the lens capsule, the cortex, and the nucleus. For the purpose of this model, each material was assumed to be linearly elastic and isotropic. Although these materials might behave in a non-linear way, as discussed by Krag & Andreassen [9], linearity was a reasonable approximation when the strain was less than 10%. Therefore isotropic linear elasticity was adopted. The mechanical properties of different materials are shown in Table 1.

The lens was anchored into the ciliary body by three sets of the zonular fibers: anterior zonules, equatorial zonules and posterior zonules. Zonular fibers were thin, smooth and stretchable. The diameter of anterior zonules and posterior zonules was about 25-60μm, and equatorial zonules about 10-15μm [12]. Few data were available on mechanical properties of the zonules. Therefore alternative approaches had been used to determine the mechanical parameters. Burd and the coleagues [4] modeled zonules as sheets with zero circumferential stiffness. However genuine zonules had no such structural continuity. Shung[5] applied pull force directly on the lens capsule so as to avoid the modeling of the zonules. In this paper, we used three sets of springs to model the zonules and they were assumed to attach the ciliary body at the same point. Referring the studies of Fisher[13], Rao and Wang [14], we set spring's stiffness as 0.3N/mm, 0.05 N/mm, 0.15 N/mm respectively.

Finite Element Model and Optical Power Universal finite element software ANSYS 8.0 was used to construct the simulation model, as shown in Figure 3. The simulation process of accommodation in this paper was as following: ciliary body, represented by zonules attachment point in our model, moved away from the lens symmetry axis and this displacement caused the zonules (springs) to stretch, then the zonules pull the lens. The lens would deform to cause the variation of its optical power.

The optical power is calculated using the conventional thick

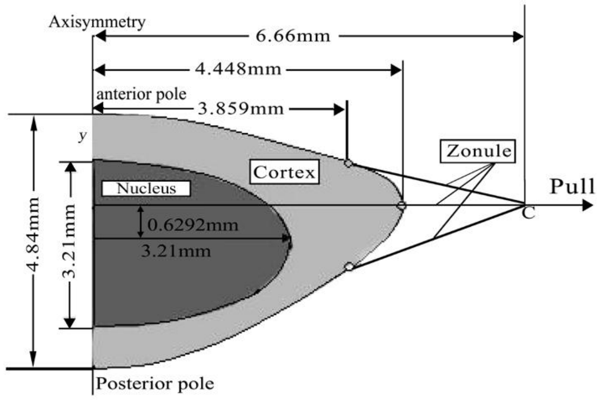

Figure 1 Lens profile and parameters

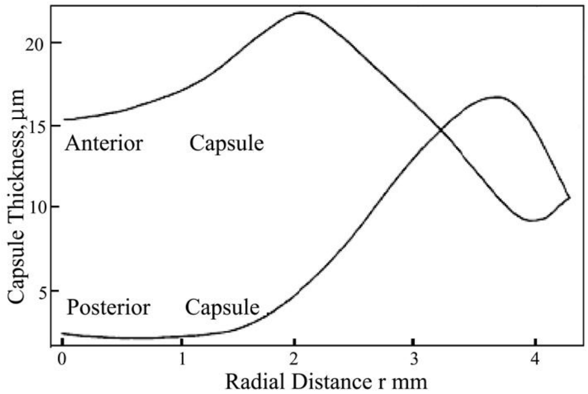

Figure 2 Thickness curve of the lens capsule

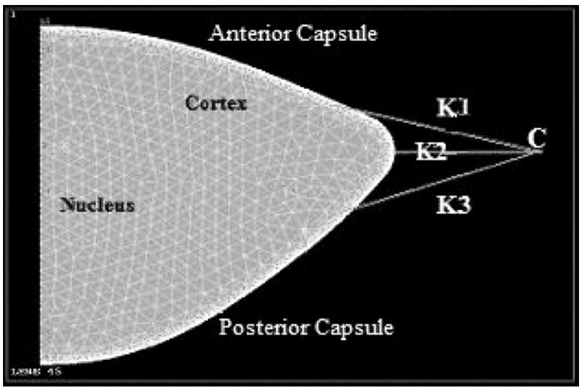

Figure 3 Finite element mesh model of the lens and zonule

Table 1 Material parameter of the lens and zonules

	Young's modulus	Poisson's ratio
Capsule	1.45 [a]	0.47 [b]
Cortex	0.000398[c]	0.49 [b]
Nucleus	0.0001[c]	0.49 [b]
Zonules	Spring Stiffness N/mm	
K1	0.3	
K2	0.05	
K3	0.15	

[a]Krag & Anderson[9]; [b]Fisher[10]; [c]Fisher[11]

lens formula $optical power = \frac{n_l - n_a}{r_a} + \frac{n_l - n_a}{r_p} + \frac{t(n_l - n_2)^2}{r_a r_p n_l}$ (1) where n_l, the refractive index of the lens, is assumed to be 1.42 and n_a, the refractive index of the aqueous and vitreous, to be 1.336; r_a, r_p are the radii of the anterior and posterior surfaces respectively and t is the thickness of the lens. The parameters r_a, r_p and t are calculated from the deformed lens figure data.

The geometry of the portion of the anterior and posterior surfaces within a circular aperture of radius 1.5mm was used to determine the optical power of the lens. A sphere fit was made through this 3mm circular zone of each surface, which is most important for vision, to calculate the radius of the central or optical zone.

In original state there is no stretch in these springs. When the attachment point moves against the lens to simulate the relaxation of ciliary muscles, the springs stretch to deform the lens. In the simulation the original state equals to the maximum accommodation state. When the ciliary body moves to the furthest position, the human crystalline lens then is believed to be without any accommodation.

RESULTS

Deformation of the Lens Under the Pull of the Zonules

Numerical simulation was carried out to study the accommodation mechanism. To study the relationship between the deformation of the lens and the displacement of the ciliary body, the following parameters were calculated: lens thickness, lens radius, the shift of lens equator plane, curvature radii of the anterior and posterior surfaces, the optical power and the force applied by ciliary body to cause the deformation. Calculations were conducted by applying a displacement to the ciliary body point (point C in Figure 3) that would correspond to the expected amplitude of movement. According to Strenk, Semmlow, Strenk &Munoz [15], the displacement was set to be in 0-0.25mm.

Simulation results suggest that, when the ciliary body moved away from the lens, the zonules stretched and pulled the lens and the anterior surface of the lens moved backward and the posterior moved forward. The lens became thinner and the radius of the lens increased. The equator plane shifted tinily toward the anterior pole. Figure 4 shows the deformed lens profile of 0.1mm displacement. It describes the typical deformation of the lens under the pull of the zonules. Figure 5 shows the linear variations of thickness and radius with displacements respectively.

As the ciliary body moved away from the lens, the curvature radius of the anterior and the posterior surfaces increased. The optical power was then calculated by (1). As shown in Figure 6, it decreased when the ciliary body moved away form the lens. This result was consistent with Shung [5] and Zhang[16].

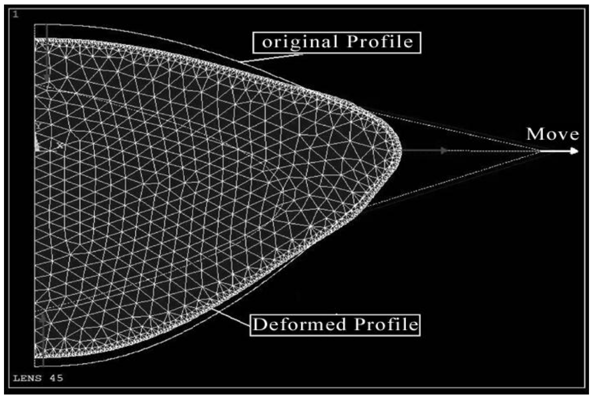

Figure 4 Lens deformation with pull displacement=0.1mm

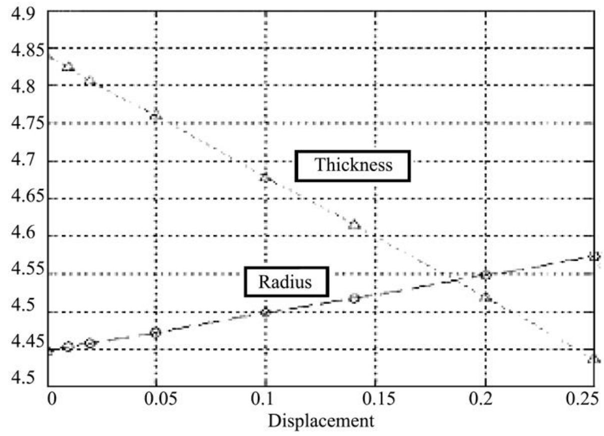

Figure 5 Lens thickness and radius variation with displacement

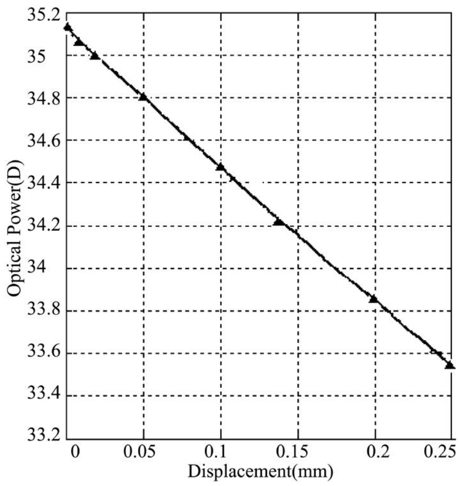

Figure 6 Variation of optical power with displacement

To analyze the function of the anterior and posterior zonules, stiffness of the equator spring was set to zero while other two springs didn't change. Then 0.2mm displacement was applied to the ciliary body. The results of numerical calculation were as following: the deformed lens' thickness t=4.542mm, radius R=4.515mm, equator plane $shift$ = 0.015mm, optical power OP=33.85D. This result suggested that the anterior and posterior zonules cooperated to keep the lens stable when accommodating. Furthermore, these two sets of zonules contributed apparently to the variation of the optical power: they brought an increment of 1.3D to the lens optical power. So it seems that the anterior and posterior zonules may be more important to the lens accommodation than the equator zonules. This may explain why the anterior and posterior zonules are thicker and tighter than the equator zonules.

The maximum strain of the lens capsule is 3.4%, which is less than 10%. As discussed in Section 2.2, isotropic linear elasticity is completely acceptable when the strain is in this scope.

Deformation of the Lens under Eye Pressure In natural state *in vivo* lens was immersed in the aqueous humor which produces eye pressure on the lens surface. The normal pressure was between 1.33kPa and 2.79kPa. The eye pressure could deform various tissues of the human eye remarkably, including the lens. Therefore it was important to study the influence of the eye pressure on the lens. An investigation had been conducted to study the influence of the eye pressure on the lens. Surface pressures varying from 1kPa to 3kPa were loaded to the outer surface of the lens respectively. The ciliary body was assumed to be fixed.

Table 2 lists the calculation results. As the pressure increased, the lens shifted tinily toward the anterior pole. This illustrated that the force on the posterior surface produced by the pressure was stronger than the force on the anterior surface according to the surface shape of the current model. So the lens moved forward. At the same time the three sets of zonules stretched more and more to hold back the lens as the lens was pushed forward. Their pull forces increased until it equaled to the push force. Then the lens stopped at a balance state.

When the pressure increased, the anterior surface moved backward and posterior surface moved forward. The lens thickness decreased and the equator of the lens extended toward the ciliary body. The radii of curvature of the anterior and posterior surfaces decreased. The optical power increased almost linearly against the increase of the pressure as shown in Figure 7. The pressure has a considerable influence on the shape of the lens so it may change the optical power remarkably.

Deformation of the Lens under the Pull and Pressure To study the effect of the pressure when the lens was pulled by the zonules, both the displacement and the pressure were applied to the presented model in this part. The analysis showed that the deformation of the lens under constant pressure was similar to that without pressure: when the displacement increased, the lens became thinner and the radius of the lens increased; the curvature radius of anterior surface increased and the curvature radius of posterior decreased; the optical power increased almost linearly.

Table 2 Parameters of deformed lens with different pressure (mm)

P(kPa)	t	R	Shift($\times 10^{-3}$)	r_a	r_p	OP(D)
0	4.840	4.448	0	5.844	3.622	36.596
1	4.488	4.482	0.0312	5.733	3.393	38.445

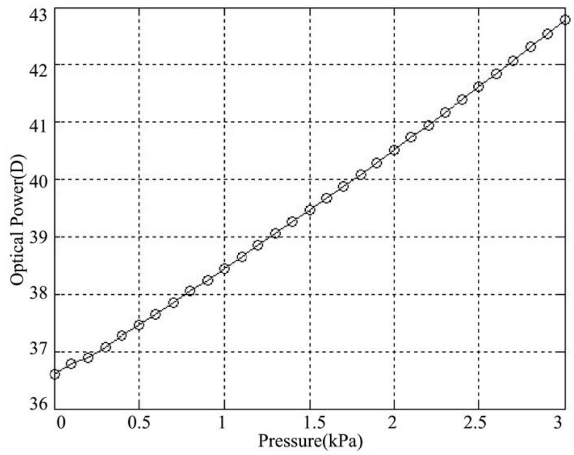

Figure 7 Variation of the optical power with pressure

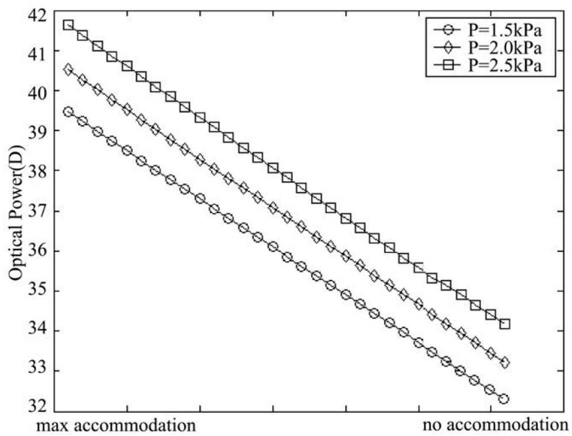

Figure 8 Lens variation with different displacements with P= 1.5, 2.0, 2.5kPa respectively

Calculations of different pressure values had also been conducted to compare the influence of different pressures. Figure 8 shows the comparison of P=1.5, 2.0, 2.5kPa. In all 3 cases the lens model behaved in the same way and only the result values of the lens parameters differed. This suggested that the influence of the pressure on the lens optical power was independent of the displacement.

The maximum strain of the capsule under the maximum displacement was 6.4%, which was still in the scope that was necessary to the assumption of linearity material property. However, it should be noted that the maximum strain of the contents (cortex and nucleus) was up to 40%. In this instance the content material may behave a nonlinearity way. So a nonlinear model may be more accurate and this expects more experimental data.

DISCUSSION

In this paper, an axisymmetrical, linear, finite element model of the human crystalline lens has been presented and has been applied to simulate the accommodation process. Results show that the optical power decreases as the zonules pulled the lens away from its axis. This result is consistent with Helmholtz's hypothesis of accommodation to some extent. Further calculation suggests that the anterior and posterior zonules not only are of great importance to the location stability of the lens during accommodating, but also contribute much to the variation of the optical power.

Another important conclusion is that the shape of the presented model lens is sensitive to the pressure on its outer surface. Even a normal eye pressure can bring a great increase to the optical power. The optical power increases as the pressure increases with a rate of about 2 Diopters per kPa. When the zonules pull the lens, the model lens behaved in the same way no matter with or without pressure and the influence of the pressure is independent.

The outcome of the current study is believed to accord with expectation. Both the modeling method and simulation results are helpful to the study of the accommodation mechanism. With new, better, experimental data becoming available in the future, numerical modeling can be developed as a successful approach in the study of accommodation.

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