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Tel:029-82245172 Email:IJO.2000@163.com www.IJO.cn

·Original article·

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]

Abstract

• AIM: Accommodation is one of the most important functions of human eye, while its mechanism is still under discussion. This paper aimed 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 are 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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[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, Chinan. ewliuzhuo@163.com

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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 decreases 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.

METHODS

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

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

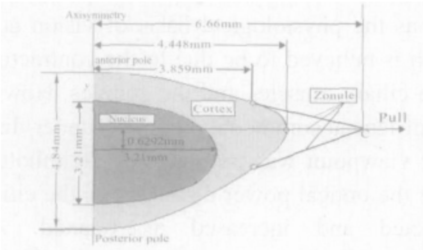

Figure 1 Lens profile and parameters

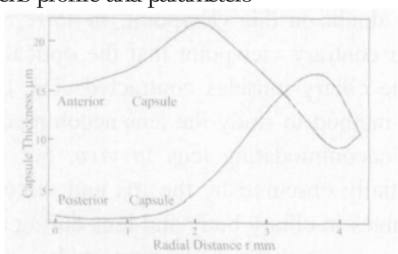

Figure 2 Thickness curve of the lens capsule

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

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]

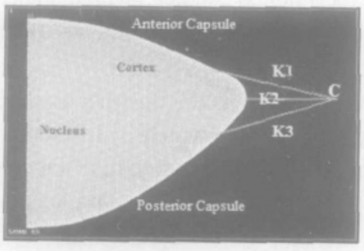

Figure 3 Finite element mesh model of the lens and zonule

The lens is anchored into the ciliary body by three sets of the zonular fibers: anterior zonules, equatorial zonules and posterior zonules. Zonular fibers are thin, smooth and stretchable. The diameter of anterior zonules and posterior zonules is about 25-60μm, and equatorial zonules about 10-15μm[12]. Few data is available on mechanical properties of the zonules. Therefore alternative approaches have been used to determine the mechanical parameters. Burd and the coleagues [4] modeled zonules as sheets with zero circumferential stiffness. However genuine zonules have 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 use three sets of springs to model the zonules and they are 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 the Figure 3. The simulation process of accommodation in this paper is as following: ciliary body, represented by zonules attachment point in our model, moves away from the lens symmetry axis and this displacement caused the zonules (springs) to stretch, then the zonules pull the lens. The lens will deform to cause the variation of its optical power.

The optical power is calculated using the conventional thick lens formula $opticalpower=\frac{n_1-n_a}{r_a}+\frac{n_1-n_a}{r_p}-\frac{t(n_1-n_2)^2}{r_a r_p n_1}$ (1) where n_1, 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.

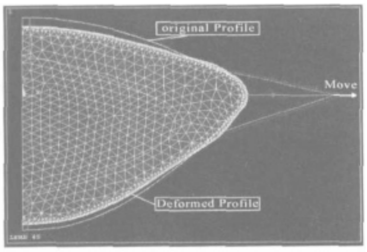

Figure 4 Lens deformation with pull displacement=0.1mm

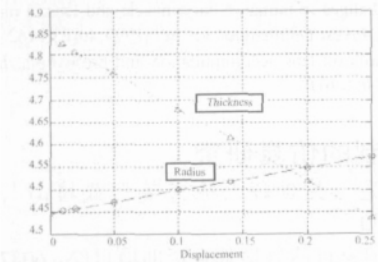

Figure 5 Lens thickness and radius variation with displacement

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 is consistent with Shung [5] and Zhang[16].

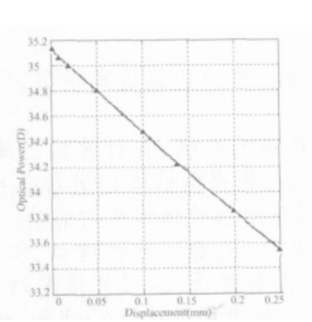

Figure 6 Variation of optical power with displacement

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 is immersed in the aqueous humor which produces eye pressure on the lens surface. The normal pressure is between 1.33kPa and 2.79kPa. The eye pressure can deform various tissues of the human eye remarkably, including the lens. Therefore it is important to study the influence of the eye pressure on the lens. An investigation has 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.

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

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

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.

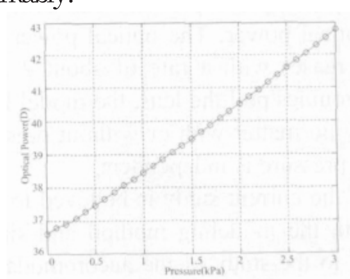

Figure 7 Variation of the optical power with pressure

Deformation of the Lens under the Pull and Pressure
To study the effect of the pressure when the lens is pulled by the zonules, both the displacement and the pressure were applied to the presented model in this part. The analysis shows that the deformation of the lens under constant pressure is 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.
Calculations of different pressure values have 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 suggests that the influence of the pressure on the lens optical power is 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) is 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.

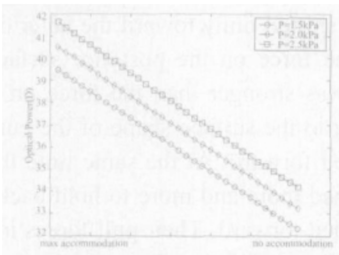

Figure 8 Lens variation with different displacements.with *P*=1.5,2.0,2.5kPa respectively

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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人眼调节机制的仿真研究

刘　卓[1,2],王博亮[2],吴世辉[3],徐秀英[2],戴培山[1],鞠　颖[2],谢杰镇[2],黄晓阳[2]
基金项目:中国国家自然科学基金资助项目(No.60371012);**中国福建省科技重点项目资助**(No.2002Y021)
(**作者单位:**[1]410073 **中国湖南省长沙市, 国防科技大学电子科学与工程学院;**[2]361005 **中国福建省厦门市,厦门大学计算机科学系;**[3]361005 **中国福建省厦门市,厦门大学医院眼科**)
作者简介:刘卓,男,博士研究生,主要研究方向:医学电子工程,虚拟器官(眼)结构和功能模拟。
通讯作者:刘卓.newl iuzhuo@163.c om
摘要
目的:建立人眼晶状体的功能仿真模型,研究人眼的调节机制。
方法:利用临床获得的数据,在计算机上建立晶状体调节的数字仿真模型,根据调节理论进行晶状体形变和调节仿真,并分析眼压对晶状体形变的影响。
结果:仿真计算表明,随着调节的增加,前、后表面向远离晶状体中心的方向移动,晶状体厚度增大,前房深度减小;晶状体的前、后表面曲率半径增加,使得屈光力增大。晶状体形态对压力变化敏感:在晶状体表面施加压力后,前、后表面在压力的作用下向赤道部移动,晶状体厚度减小;前后表面曲率半径增大,赤道半径增大;屈光力随着压力的增大而增大。
结论:仿真研究支持了 Hel mhol tz **的调节理论,与公认的调节事实相符合,表明了仿真研究是有效的研究方法。**
关键词:晶状体;调节;仿真