Geometry, optics and mechanical modelling of the human lens during accommodation

Towards developing an accommodative intraocular lens

English summary

Aims of the present study

In order to accommodate, the optical power of the human lens increases. In principle, the changes that occur in the optical power of a lens are two-fold. First of all, the changes in geometry (i.e. in the thickness and radii of curvature) influence the optical power of the lens. Secondly, the refractive index influences the direction and length of the optical path, and consequently also influences the optical power of the lens. During accommodation, the changes in optical power of the human lens are caused by a mechanical action of the ciliary muscle. However, with age the human eye loses its ability to accommodate; this is referred to as presbyopia, the exact causes of which are not yet known.

The first part of the present thesis focused on obtaining more insight into the accommodation mechanism, and consequently the origin of presbyopia. In order to study the changes that occur in the geometry and refractive index, model-based measurements of the geometry and refractive index of the human lens were carried out in a group of five healthy subjects at different levels of accommodation. Furthermore, the changes in geometry were used to study the mechanical aspects that contribute to the change in optical power. Therefore, mechanical modelling was performed to obtain more insight into the accommodation mechanism in people at a young age.

In most cases, presbyopia and ametropia are currently corrected by (multifocal) spectacles or contact lenses. However, at an elderly age there can be cataract formation, and the lens becomes opaque. Most intra-ocular lenses (IOLs) that are implanted to restore vision have a fixed focal power, and therefore do not accommodate, but an accommodative IOL could not only provide a solution for cataract and ametropia, but also for presbyopia. However, the requirements for an IOL that could be used to restore accommodation and guarantee spectacle-independence are stringent. Firstly, the accommodative power of the accommodative IOL must be large, in order to ensure comfortable reading. Secondly, it is necessary to have a predictable outcome of the patient's refractive error. An accommodative IOL that restores accommodation, but has no predictable disaccommodated refractive power after implantation, does not guarantee spectacle-independence. Moreover, an accommodative IOL should preferably also be capable of compensating corneal astigmatism, and should have an optical quality that is similar to the quality of a present generation monofocal IOL in all accommodative states. Finally, the accommodative IOL should preferably be operated by the human ciliary muscle.

The second part of this thesis described how we developed an accommodative IOL as a solution for cataract, ametropia and presbyopia, using the knowledge obtained in the studies described in the first part of this thesis.

9.1 Geometry, optics and mechanical modelling of the human lens during accommodation

Changes in geometry of the lens during accommodation

During accommodation the thickness of the lens increases and the radius of curvature of the anterior and posterior central area decreases, resulting in an increase in optical power. According to the Helmholtz accommodation theory (Von Helmholtz, 1855), this deformation is caused by the ciliary muscle release of zonular tension. However, it is not exactly known whether the deformation of the lens is due to the elasticity or the compressibility of the lens material.

A change in the surface area of the capsular bag could indicate that the elasticity of the capsular bag plays an important role in accommodation. On the other hand, a change in the volume of the lens could indicate that decompression of the internal lens material causes the accommodative changes. The objective of the study described in Chapter 2 was to determine the volume of the lens and surface area of the capsular bag, and to investigate whether there is a change in these quantities with accommodation. For that purpose 3D magnetic resonance imaging (MRI) was used to determine the 3D shape of the lens as a function of accommodation in five healthy subjects. The 3D shape of the lens was described by cross-sectional geometry with five physical parameters. From this parametric geometry the surface area of the capsular bag and the volume of the lens were estimated. Scheimpflug imaging (Dubbelman, Van der Heijde and Weeber, 2005) was used to validate the MRI results. In accordance with the Helmholtz accommodation theory, there was a decrease in the equatorial radius of the lens with accommodation, while there was an increase in the thickness and the central anterior and posterior curvature. During accommodation we found a decrease in the surface area, but no significant change in volume of the lens. This indicates that the internal human lens material can be assumed to be incompressible, and undergoes elastic deformation. Moreover, the change in the surface area indicates that the capsular bag also undergoes elastic deformation.

3D MRI measurements do not provide a well-defined, visual representation of the embryonic nucleus, but the nucleus is completely visible and clearly characterized with Scheimpflug imaging. It is the thickness of the nucleus that changes most during accommodation compared to the overall changes in the thickness (Dubbelman, Van der Heijde, Weeber and Vrensen, 2003). Chapter 3 presented a new method in with which a parametric measurement of the 2D shape of the human lens nucleus can be obtained from Scheimpflug images. For five subjects, the results show that during accommodation the nucleus became more convex and that the central thickness increased, whereas the equatorial diameter decreased. This decrease in equatorial diameter of the nucleus with accommodation is in accordance with the Helmholtz accommodation theory. Assuming that the nucleus is rotationally symmetric, the volume of the nucleus can be estimated by integrating around the circumference. The volume of the nucleus showed no significant change during accommodation in any of the subjects.

In conclusion, during accommodation there was no change in the volume of the complete lens or the volume of the embryonic nucleus, presumably due to the fact that the human lens consists of incompressible material with a Poisson's ratio that is near 0.5.

Changes in refractive index of the lens during accommodation

Gullstrand hypothesized that the change in power of the lens that is needed for accommodation does not result from changes in lens thickness and surface curvature alone, but also from changes in the distribution of the refractive index within the lens. As a result, there should be an increase in the equivalent refractive index with accommodation. He called this process the intra-capsulary mechanism of accommodation. Chapter 4 described how the theory of Gullstrand (1909), i.e. that the equivalent refractive index of the human lens increases with accommodation, was verified experimentally. The shape of the cornea and the lens were measured with corrected Scheimpflug imaging in a group of five healthy subjects at different accommodative stimuli. Subsequently, using the same accommodative stimuli, aberrometry was used to obtain objective measurements of the accommodative response and amplitude. After measuring the axial length, it was possible to calculate the equivalent refractive index with the step-along method. Furthermore, the geometry of the nucleus (Chapter 3) was derived from the Scheimpflug measurements to construct a two-compartment model, as proposed by Gullstrand.

In all five subjects, we found no significant change in the equivalent refractive index of the lens as a function of accommodation. The accommodative response appeared to be lower than the accommodative stimulus (i.e. accommodative lag). Furthermore, it appeared to be possible to model the optical power of the lens, based on the geometry of the cortex and nucleus. Both the one-compartment model and the two-compartment model showed that it is possible to describe the changes during accommodation with constant refractive indices. The refractive indices of the two-compartment model are more in line with the physiological measurements of the refractive index of the human lens than the equivalent refractive index of the one-compartment model.

In order to compute the equivalent index of refraction, as described in Chapter 4, a website was launched: www.eyepower.nl . Ray-tracing was used to visualize the optics of the eye and it was possible to interactively change the geometry of the eye. It was also possible to change the power of an implanted monofocal IOL in order to determine the post-operative refractive error.

Mechanical modelling of the accommodation process

In order to be able to design an accommodative IOL, it is necessary to know the forces acting on the lens that are produced by the complex of ciliary muscle and zonular fibres. However, the exact magnitude and direction of these forces is not known, for two reasons. Firstly, no method or device has yet been developed that is capable of measuring force during accommodation in vivo. Secondly, the zonular fibres transfer the ciliary muscle force to the capsular bag, but there is a lack of information about the mechanical properties, the number and the geometry of these fibres.

Chapter 5 described a new method in which finite element (FE) modelling was used to estimate the magnitude of the external force which moulds the lens into an unaccommodated shape of a typical 29 year-old human lens. To investigate the influence of the anterior, posterior and central zonular fibres insertion regions, three models with different configurations were constructed. All three configurations appeared to be capable of inducing the required accommodative changes in the lens. The configuration of the zonular fibres insertion regions had no significant influence on the size of the external force. Based on material properties described in the literature, the estimated summed net force for each of the three models was approximately 0.08 N.

The objective of the study described in Chapter 6 was to determine the accommodative force on the lens at different ages, and to find out whether there is a change in this force with age. In this chapter the method described in Chapter 5 was used to estimate the force on the lenses of an 11, 29 and 45 year-old human eye. Furthermore, the parametric shape of the nucleus, derived in Chapter 3, was incorporated in the simulations, together with new material properties described in the literature. The force on the lens appeared to be preserved with age, with only a slight increase to a value of approximately 0.06 N. In conclusion, the preservation of the net force delivered by the extralenticular ciliary body indicates that the causes of presbyopia must mainly be ascribed to lenticular changes. The preservation of accommodative force as a function of age is useful as a reference for the development of an accommodative IOL that could restore accommodation.

9.2 Development of an accommodative IOL

The first part of this thesis described how we obtained more knowledge about the geometry, refractive index and mechanics of the human accommodation process. We were able to use this knowledge to develop a method to restore accommodation. Therefore, the second part of the thesis focused on the development of an accommodative IOL that meets the requirements for a spectacle-independent solution for presbyopia.

Chapter 7 described the development of an accommodative IOL ("the Turtle lens") with a rotating focus mechanism and a mechanical frame that could operate within the range of ciliary muscle contraction. The concept design was optically and mechanically optimized for a typical 60 year-old human eye, and ray-tracing showed that the modulation transfer function (MTF) of the Turtle lens in different accommodative states did not deviate to any great extent from the MTF of a monofocal IOL. We produced prototypes to test the mechanical performance in an enucleated pig's eye, using a laboratory lens-stretching device that mimics the action of the human ciliary muscle. Changes in focal length during stretching were determined by means of laser-based ray-tracing and video-recordings. During the stretching experiments the prototype of the Turtle lens achieved 8 D of accommodation.

In conclusion, most of the requirements for an accommodative IOL, through which spectacle-independence can be achieved, can be met. The mechanical frame, in combination with the rotating focus principle, can be used to develop an IOL that restores accommodation with a large and predictable accommodative amplitude. By using stop-devices, the base power can be varied in steps of 0.5 D, according to the required refractive outcome of the patient. Astigmatism and higher order aberrations, such as spherical aberration, could be compensated by the optical design. However, both the mechanical and the optical design need further optimization to improve the optical quality and functionality of an accommodative IOL.

The Turtle lens was developed in collaboration with Advanced Medical Optics Inc., which had the rights to claim intellectual property. Chapter 8 presents the application for a patent with the various principles and embodiments of the new accommodative IOL concept.

Reference list

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