Mechanics of Human Accommodation and Presbyopia
Summary

The aim of this study was to determine the role of the mechanical properties of the lens matrix in the accommodative process, and especially how they influence the deformation of the crystalline lens during accommodation.

In a first exploratory analysis, a mechanical model was developed describing the mechanism of accommodation, based on existing literature data. The model consisted of three components: the lens matrix, the lens capsule and a schematic representation of the zonular fibers. For the young eye, this model predicted an acceptable amount of accommodation, which was reasonably close to what is measured clinically. For the older eye the predicted accommodative amplitude was considerably larger than clinical values, showing little signs of presbyopia. This deviation from the clinical situation could have a number of causes, the most important ones being (1) the stiffness values of the lens from the literature are not reflecting the true mechanical properties of the crystalline lens, (2) presbyopia is not caused by the increasing stiffness of the lens and (3) the modeling methodology is not adequately simulating the actual situation. The first two points are explicit subjects in this study. The last point has been briefly touched upon in chapters 6 and 7, and will also be discussed further on.

The exploratory analysis showed that when a model uses different stiffness values for the nucleus and the cortex, this can have a relative large effect on the accommodative amplitude in the simulation.

In a further explorative analysis, variations in the model have been investigated. The variations consisted of the introduction of Wieger’s ligament, an age-dependent stiffness of the lens capsule and a pre-stressed lens capsule and lens matrix at the start of the simulation. Introducing Wieger's ligament in the model changed the relative contribution of the anterior and posterior lens surface to the total power change of the lens. With Wieger's ligament in the model, the anterior lens surface contributed more to the total change in lens power, bringing the simulation results closer to clinical observations. An increase of the stiffness of the capsule resulted in an increase in required zonular force, but did not lead to significant changes in accommodative amplitude. A pre-stress in the crystalline lens
hardly influenced the accommodative amplitude or the required zonular force.

In a next phase of this study the mechanical properties of crystalline lenses of varying ages were determined using a dynamic mechanical analysis (DMA). DMA was performed on 39 human lenses, ranging in age from 18 to 90 years. The lenses were stored at -70 °C before being measured. The influence of freezing on the mechanical properties was determined using pairs of porcine lenses, with one lens measured directly after enucleation and the other after being stored frozen. The influence of freezing, as well as the measurement reproducibility and repeatability were small compared to the large differences with age that were found. The lenses exhibited a distinct viscoelastic behavior. The storage and loss compliance depended strongly on age and decreased a factor 1000 over a lifetime. The stiffness of the lens material increased exponentially with age.

In a further study, using fewer lenses, the mechanical properties of the lens were measured locally within the lens. In order to do so, the lens was cut in half along the equatorial plane. The stiffness was measured using an oscillating indenter, penetrating the lens at different locations in the cutting plane. The resistance to oscillation was measured at different frequencies. A full frequency sweep was however not possible, due to the expected influence of sample inertia on the measurement. Nevertheless, the results demonstrated that the dynamic shear modulus varied strongly with measurement location for all tested lenses. The stiffness gradient depends on the age of the lens. The results of the 10 measured lenses (age range: 19 to 78 years) indicate that the stiffness at both the center and the periphery increase with age, but at a different rate. At young age, the nucleus is softer than the cortex, and at older age, the nucleus is stiffer than the cortex.

The measured mechanical properties of human lenses were subsequently implemented in a finite elements model of accommodation. Compared to the exploratory model, 3 aspects were different in the new model:

(1) The surface curvatures of the lens were now derived from in vivo measurement data from Dubbelman et al.\textsuperscript{1} of lenses in the maximum accommodated eye. From these data, a regression was
made to arrive at an average shape and thickness of the 40-year-old lens. The lens surfaces were aspherical.

(2) The loading parameters were adjusted. While in the explorative studies, the lens equator was stretched by 7% for all ages, now the lens was stretched with an equal force for all ages. The force was derived from the force required to stretch the 40-year-old lens by 7%.

(3) The new lens stiffness values were implemented, both the results of the measurements on entire lenses as well as the results of the local stiffness measurements. For the implementation of the local stiffness, the interior of the lens was modeled in concentric regions, each region having a uniform stiffness.

Thus, three variations of the model were defined, depending of the stiffness profile in the lens: (1) incorporating the classic uniform stiffness values measured by Fisher\(^2\), (2) incorporating a uniform stiffness as measured by dynamic mechanical analysis on entire lenses and (3) incorporating the stiffness gradient obtained from local stiffness measurements. For the 40-year-old lens, all models predicted acceptable amounts of accommodation, reasonably close to clinical values. Model (1) demonstrated a very small decline in accommodative amplitude, similar to that shown in the original explorative analysis. Model (2), incorporating a uniform stiffness that increases exponentially with age, also showed just a small and almost linear decline of accommodative amplitude with age. Model (3) however showed an accelerated decline of accommodative amplitude after the age of 40 years approaching zero at the age of 60 years. These results demonstrate that the change in stiffness gradient is far more important than the magnitude of the stiffness itself. The accelerated decline in accommodative amplitude starts at the moment in life when the nucleus becomes stiffer than the cortex.

In model (3), with the stiffness gradient incorporated, the deformations within the lens were further analyzed. It was demonstrated that the thickness change during accommodation takes place mainly in the nucleus of the lens. This behavior is very similar to that found clinically, as measured by Dubbelman and co-workers\(^3\) using Scheimpflug images.
The current study provides evidence that the gradient stiffness of the lens material can fully account for the loss of accommodation with age. The model predicts presbyopia about 10 years later than found clinically. This discrepancy could be due to shortcomings in the model and in the input data. The stiffness gradient was determined using only 10 human donor lenses, which also had been frozen prior to testing. On the other hand, the discrepancy could also indicate that more factors than were modeled in this study play a role in the development of presbyopia. Factors, like geometric changes with age, could be incorporated in a future mechanical model.

References