Modelling of the human lens complex under cataract surgery.

Maria Teresa Andrade Santos Leitão Cardoso[1]

Instituto Superior Técnico, Lisbon, Portugal
[1]e-mail: teresaaslcardoso@tecnico.ulisboa.pt

ABSTRACT

A cataract is a disease that affects the crystalline, when it loses to much transparency and becomes opaque, leading to a blurred vision, and in the extreme to blindness. With the aging of the population, the incidence and prevalence of cataracts is increasing, as well as the number of procedures performed to remediate to it. The crystalline complex, including the crystalline, the capsular bag, the zonular fibers and the ciliary body, is of extreme importance since it allows the eye to focus objects. Nowadays the most common solution available for cataract is the complete removal of the cataract, followed by an implant of an intraocular lens (IOL), turning it into a pseudophakic eye. With the increase of cataract surgeries, an increase in post-operative complications arose, the most serious being posterior chamber IOL dislocation. Computational models of the complete crystalline complex were already built, but none after cataract surgery. In this work, through the software Abaqus®, an axisymmetric Finite Element (FE) Analysis of the crystalline complex during the process of accommodation under cataract surgery, with an IOL implant is proposed, to understand if there is a mechanical influence on post-operative complications. An increase of force and stress in the zonules was verified in the pseudophakic eye compared to the complete eye, that could explain why years after surgery zonules would break leading to an IOL dislocation. The model proposed in this work is innovative in this field and would be a good complement for the already existing work about the crystalline complex.
Keywords: cataracts, intraocular lens, axisymmetric, membrane, capsular bag, zonular fibers.

1. Introduction

Cataract is a disease that leads to visual impairment, and eventually to blindness, worldwide. With the aging of population, the incidence and prevalence of cataract is increasing, as well as the number of procedures performed to remediate to it, consequently. Prokofyeva made a literature review in 2013, using data between 1990 and 2009, and concluded that in Europe the prevalence of this disease increased from 5% in population between 52-62 years-old and from 30% for 60-69 years old to 64% in population above 70 years-old (Prokofyeva et al., 2013). In the United States, the same previsions are made. A projection of the prevalence of cataracts has been made for the years 2030 and 2050, with the number of cases going from 38 million to 50 million (National Eye Institute, 2010). Cataract surgery with intraocular lens (IOL) implantation has been quickly evolving over the years, with the development of new technology and techniques, such as phacoemulsification and new materials for IOLs, making it a safer procedure than it was a couple of decades ago. Following cataract surgery, few complications can appear, the most serious being posterior chamber IOL dislocation since it leads to more complex surgeries, although it is uncommon (Al-Halafi et al., 2011). The following *in silico* studies shall help understand the mechanics of the IOL dislocation, and study the parameters that could influence this complication, due to their increasing incidence following the increase of procedure performed to remove cataracts.

The Human Eye Lens Complex

The human eye lens complex is composed by four main components: the capsular bag, the crystalline lens (divided in cortex and nucleus), the zonular fibers (or zonules) and the ciliary body. This complex is of extreme importance in the human visual system since it allows the eye to focus objects, i.e., to accommodate. The crystalline lens is a transparent and flexible structure enclosed inside a thin membrane with a thickness of about 10 μm, even though Fisher and Pettet (1972) showed it slightly changes with age and position, the capsular bag, and is connected to the ciliary body by the zonular fibers, at the zonular lamella. The zonules are known to be separated in three distinct groups, all around the circumference of the lens: the anterior, the equatorial and the posterior group. They are considered as suspensory ligaments which hold the lens in position, but also reshape it during accommodation.

A few theories about accommodation have risen and were not always in concordance. The most popular one was the Helmholtz's theory (Southall, 1962) that stated that in the unaccommodated (or disaccommodated) state, the lens was held in a state of radial tension by all the zonules. When beginning the process of accommodation, the ciliary body contracted leading to a reduction of tension in the zonular fibers and to an increase of curvature of lens surfaces and optical power, until reaching the fully accommodated state. Opposed to Helmholtz's, stood Schachar's theory (Schachar, 1992) stating that when going from the unaccommodated to the accommodated state, the contraction of the ciliary body lead to an increase of tension in the zonular fibers, i.e., stating that the zonules had a direct effect on this process. In a mechanical point of view, Helmholtz claimed that the stress-free state of the lens complex was when it stood in an accommodated state, with no stresses on the zonular fibers, whereas Schachar stated that this stress-free state occurred in the unaccommodated state. Figure 1.1 shows an eye in the accommodated and in the unaccommodated state.

Understanding the mechanisms of accommodation was very relevant in order to study some complications regarding the crystalline lens and its associated structures. The main one, that is going to be discussed in this work, usually occurs in late adult life, when the crystalline lens loses too much transparency and becomes opaque: it is said to be a cataract. This results in the reduction of the transmission of light and in scattering light, leading to a blurred vision, and in the extreme, when not treated in time, to blindness. Nowadays, the most common solution available is the complete removal of the cataract, i.e., of the crystalline lens, followed by an implant of an IOL to replace it (Ascaso & Huerv, 2013). However, if the cataract does not affect everyday activities, it does not need to be operated.

The main objective of this work was to propose a mechanical model of the IOL-capsular bag complex after cataract surgery. Furthermore, knowing that late IOL-capsular bag dislocation was one of the most serious problems after this procedure, we aimed to study the stresses in the capsular bag and in the zonular fibers through a Finite Element (FE) Analysis, to understand when did the zonules break and lead to the dislocation of all the complex. Few parameters, as the diameter of the capsulotomy, the position of the IOL, and materials of the IOL were studied to see if they had an influence on this process and to seek the best configuration to avoid this complication.

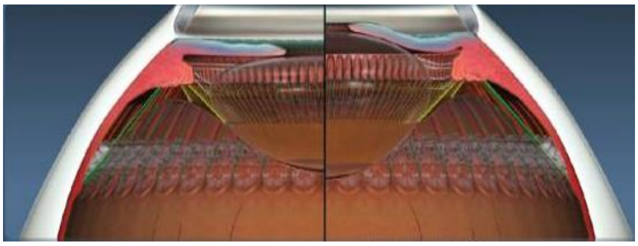

Figure 1.1. View showing half the eye (left) in an unaccommodated state and the other half (right) in an accommodated state. Adapted from Goldberg (2011).

2. Methods

A few sets of experiences were made in a computational FE axisymmetric model in Abaqus®. The axisymmetric model helped us achieve a three-dimensional-like (3D) result with less computational complexity, using a simple cross-section of the human lens, since the loading conditions are axially symmetric.

Lens and IOL's Geometry

The first model built in Abaqus® represented the capsular bag, the cortex, the nucleus and the equatorial zonules of the human lens complex, as shown in Figure 2.1. The crystalline, i.e., the cortex and nucleus, had both a perfect ellipsoid shape, with the coordinates of the major ($R_{nucleus}$ and R_{lens}, for the nucleus and cortex, respectively) and minor axis (corresponding to the thickness of the lens, T_{lens}, and to the thickness of the nucleus, $T_{nucleus}$) adapted from the radii used by Lanchares et al. (Lanchares, Navarro, & Calvo, 2012) in their work. Based in a linear regression by Burd et al. (Burd et al., 2002) it was also possible to compute the radius of the ciliary body (R_{total}), and consequently to compute the length of the equatorial zonules (R_{zon}) to use in this work. The capsular bag had the same outline as the cortex, to fit perfectly around it. The cortex and nucleus were modelled as solid homogeneous closed shells, whereas the capsular bag and the zonules as membranes, with constant thicknesses of 10 μm (Liu et al., 2015) and 40 μm (van Alphen & Graebel, 1991), respectively.

The following models of pseudophakic eyes after cataract surgery, had an IOL replacing the cortex and nucleus of the crystalline after their extraction, and differed in their geometry in the diameter of the capsulorhexis (Φ_{ccc}). As Langwińska-Wośko (Langwińska-Wośko et al., 2011) proved that small ones had great impact on the development of PCO after surgery, it was interesting to see if their diameter could also have an impact on the IOL-capsular bag dislocation. For this purpose, pseudophakic eyes with small and large capsulorhexis were modelled, i.e., with 72.73% and 81.82% of the diameter of the IOL optic, respectively. Since the models were built axisymmetrically, the capsulorhexis could only be a continuous curvilinear capsulorhexis. The cross-section of the lens that was drawn for this axisymmetric model was based on the cross-section geometry of a one-piece IOL (Alcon SN60WF) described by Sheehan et al. (Sheehan et al., 2012), and is described in Figure 2.1. R_{optic} corresponded to the radius of the optic of the lens, T_{optic} to the thickness of the optic and T_{haptic} to the thickness of the haptics.

Material Properties

Based on previous studies (Wang et al., 2017)(Weeber & van der Heijde, 2008), all materials of the human crystalline were defined as linear isotropic and quasi-incompressible. The Young's moduli and Poisson's ration of the cortex and the nucleus were based on the study of Wang et al. (Wang et al., 2017) and the capsular bag and zonules based on Weeber & van der Heijde (2008). Three different materials were tested for the one-piece IOL, hydrophilic acrylic, hydrophobic acrylic and PMMA, since they are the most used nowadays. The mechanical properties of those materials came from an experimental study performed by Bozukova et al. (Bozukova et al., 2015).

Loads/Boundary Conditions/Interactions

The accommodation process was first simulated using the model of accommodation proposed by Helmholtz (Southall, 1962), with the accommodated state of the lens being the stress-free state of the model. Then, to mimic the disaccommodation of the crystalline, an outward displacement of 0.5 mm, was applied at the tip of the equatorial zonule, where it should be anchored in the ciliary body, that had a maximal change in diameter between 1 mm and 1.2 mm (Wang et al., 2017). Furthermore, for the pseudophakic eye, to simulate the centripetal force towards the center of the opening of the capsulorhexis, a concentrated traction force (TF) was applied. Since no values *in vivo* values for this force were found in the literature, few cases were studied, with forces going from zero to values bigger than the reaction force at the zonules. An important aspect to highlight in axisymmetric models, was that prescribed nodal loads or reaction forces were the total values of these loads or forces, integrated along the circumference, around the axis of symmetry.

In axisymmetric models, there were automatic boundary conditions defined on the axis of symmetry (Y-axis) that constrained the nodes lying on it in the X-direction, i.e., they can only move up- or downward. In light of that, the only part that needed to be manually constrained was the equatorial zonule, that could only be moved in the X-direction, in all the models, before and after cataract surgery.

The interactions occurring between the capsular bag and the crystalline cortex, were based on the assumptions made by Bassnett et al. (Bassnett et al., 1999) saying that the attachment of one to another is strong enough to resist all forces created during the process of accommodation, leading us to assume a tie between both of these components. Since the capsular bag sealed itself to the IOL after surgery, a tie was also considered between the IOL and the capsule (Ascaso & Huerv, 2013).

Description of Models

With the purpose of studying stresses in the capsular bag, in the zonules and in the IOLs, the change in length in the radial direction (in the X direction) and the resulting forces at the tip of the zonules (RF), a set of 25 models of pseudophakic eyes were built. Since no such FE models were found in the literature, it was important to study the variation and influence of few parameters, such as diameter of the capsulorhexis, the IOL material and the traction force exerted at the opening of the capsulorhexis, on the model. Considering the eye before surgery as M1, the features of all the other models are summed up in Table 2.1. For the traction force, since there was no available information on its values in vivo, some hypothetic values were tested based on the resulting force at the tip of the zonules when no traction force was applied, with smaller, equal or higher values than this RF.

Table 2.1. Description of all the pseudophakic models discussed in this work, differing in the diameter of the capsulorhexis, their IOL materials and traction forces (TF) at the opening of the capsulorhexis.

Name	Φ_{ccc}	**IOL Material**	**TF (N)**
M2	4	Hydrophilic acrylic	0
M3	4	Hydrophobic acrylic	0
M4	4	PMMA	0
M5	4.5	Hydrophilic acrylic	0
M8	4	Hydrophilic acrylic	0.7
M11	4.5	Hydrophilic acrylic	0.7
M14	4	Hydrophilic acrylic	RF8
M20	4	Hydrophilic acrylic	0.15

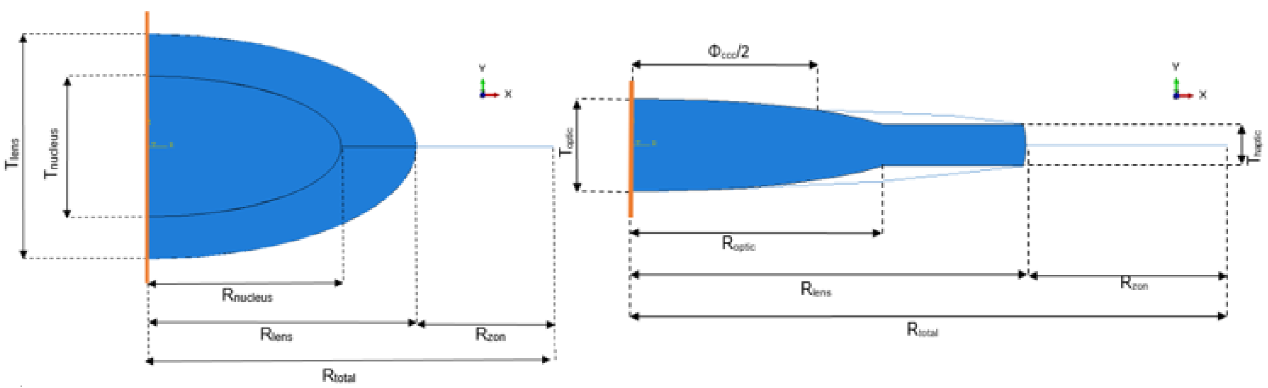

Figure 2.1. On the left, geometry of the complete crystalline complex. On the right, geometry of the pseudophakic eye. In both models, the orange line represents the axis of symmetry.

3. Results

The outcomes of the simulations after the validation of the models will be presented and compared. For each model, the von Mises stress in the zonules (S_Z), in the capsular bag (S_{CB}) and in the IOL (S_{IOL}), were assessed, as well as the radial displacement (δr) and the resulting force at the tip of the zonules (RF_Z). All the models built had the purpose to let us compare different models for pseudophakic eyes, with different diameters of capsulorhexis, different materials for the one-piece IOLs and with different traction forces towards the center of the capsulorhexis, that simulated part of the process of fibrosis.

Post-Surgery

A comparison between the eye before (model M1) and after surgery with a small capsulorhexis, a hydrophilic acrylic IOL and no traction force (model M2) was possible.

The values of stresses, radial displacement and resulting force are shown in Table 3.1 for both models. The values of stresses in the zonular fibers is almost the double from *M1* to *M2*, going from an average value of 4.7×10^{-2} MPa to 8.9×10^{-2} MPa, and from the crystalline to the IOL it substantially increased 30 times from an average value of 1.9×10^{-4} MPa to 5.8×10^{-3} MPa, whereas in the capsular bag the values decreased, going from average values of 8.0×10^{-2} MPa to 1.9×10^{-3} MPa. The radial displacement in *M2*, equal to 7.3×10^{-3} mm was almost fifty times smaller than in *M1*, 3.5×10^{-1} mm. Another value that increased from *M1* to *M2* was the resulting force at the tip of the zonular fibers, with computed values of 7.1×10^{-2} N and 12.8×10^{-2} N for the model before and after surgery, respectively. All these outcomes were expected with the increase of stiffness of the three IOL materials in comparison with the natural cortex and nucleus of the crystalline.

With a maximum of 1.5×10^{-1} MPa, the higher stress in *M1* was located on the capsular bag, whereas in model *M2* it was on the zonular fibers with a value of 9.7×10^{-2} MPa.

Table 3.1. Maximum values of von Mises stresses in the zonular fibers, capsular bag and crystalline/IOL, as well as radial displacement and resulting force at the tip of the zonular fibers for the complete eye (M1) and a pseudophakic eye (M2).

Model	Variables	Maximum	Average Value
M1	S_Z (MPa)	4.7×10^{-2}	4.7×10^{-2}
	S_{CB} (MPa)	1.5×10^{-1}	8.0×10^{-2}
	S_{IOL} (MPa)	2.1×10^{-3}	1.9×10^{-4}
	$δ_r$ (mm)	-	3.5×10^{-1}
	RF_Z (N)	-	7.1×10^{-2}
M2	S_Z (MPa)	9.7×10^{-2}	8.9×10^{-2}
	S_{CB} (MPa)	3.7×10^{-2}	1.9×10^{-3}
	S_{IOL} (MPa)	4.4×10^{-2}	5.8×10^{-3}
	$δ_r$ (mm)	-	7.3×10^{-3}
	RF_Z (N)	-	12.8×10^{-2}

Influence of the Stiffness of the IOL

To study the influence of the stiffness of the IOL in the pseudophakic eye, a comparison between models *M2*, *M3* and *M4* was performed. These three models had the same $Φ_{ccc}$ and TF, equal to zero, but differed in their IOL material and consequently, in their stiffness. The results drawn in this section can be drawn for every other three sets of models, that only differ in IOL's stiffness.

Since the PMMA lens was at least 500 time stiffer than both acrylic lenses, the expected outcome would be that it would support more stress in it with a consequent decrease of stress in the capsular bag. Whereas the general decrease of stress in the capsular bag was very slight between the hydrophilic and the hydrophobic acrylic lens, with average values going from 1.9×10^{-3} MPa to 1.4×10^{-3} MPa respectively, an accentuated change was clearly seen in model *M4*, with an average value of 8.9×10^{-6} MPa being 150 times lower than in *M2* and *M3.* With the increase of stiffness of the IOL, a slight increase of the von Mises stress on the zonules was also noticeable, in the order of 1%, as well as a slight increase of the resulting force in the zonules, in the same order. With the increase of stiffness in the IOL, more resistance to the equatorial pull in the zonules in the materials would be encountered, leading to a big decrease of radial displacement in the IOL, with the one in model *M4,* 1.2×10^{-5} mm, being 6000 times higher than in the other two models, 7.3×10^{-3} mm for the hydrophilic and 5.0×10^{-3} mm for the hydrophobic acrylic lens.

In Table 3.2, all the values for the outcomes are shown, and the values with the biggest changes noticeable are highlighted.

Table 3.2. Maximum values of von Mises stresses in the zonular fibers, capsular bag and crystalline/IOL, as well as radial displacement and resulting force at the tip of the zonular fibers for models M2, M3 and M4.

Model	Variables	Maximum	Average Value
M2	S_Z (MPa)	9.7×10^{-2}	8.9×10^{-2}
	S_{CB} (MPa)	3.7×10^{-2}	**1.9×10^{-3}**
	S_{IOL} (MPa)	4.4×10^{-2}	5.8×10^{-3}
	$δ_r$ (mm)	-	7.3×10^{-3}
	RF_Z (N)	-	12.8×10^{-2}
M3	S_Z (MPa)	9.8×10^{-2}	8.9×10^{-2}
	S_{CB} (MPa)	3.3×10^{-2}	**1.4×10^{-3}**
	S_{IOL} (MPa)	4.3×10^{-2}	5.9×10^{-3}
	$δ_r$ (mm)	-	5.0×10^{-3}
	RF_Z (N)	-	12.9×10^{-2}
M4	S_Z (MPa)	9.9×10^{-2}	9.0×10^{-2}
	S_{CB} (MPa)	2.6×10^{-4}	**8.9×10^{-6}**
	S_{IOL} (MPa)	4.4×10^{-2}	6.1×10^{-3}
	$δ_r$ (mm)	-	1.2×10^{-5}
	RF_Z (N)	-	12.9×10^{-2}

For these three models, the maximum values of stresses were in the zonules, with values of 9.7 x 10^{-2}, 9.8 x 10^{-2} and 9.9 x 10^{-2} MPa for the hydrophilic, hydrophobic acrylic and PMMA IOL, respectively.

Influence of the Traction Force

To study the influence of the traction force on the capsulorhexis on the pseudophakic eyes, models *M2*, *M8*, *M14* and *M20* were compared. They all had a one-piece IOL made of hydrophilic acrylic and the same Φ_{ccc} but differed in the traction force that was applied. It increased from 0 N to 0.15 N, from model *M2* to model *M20.* The outcomes for this parametric study are depicted in Table 3.3.

With the increase of the traction force, no change in stress in the zonules nor in the resulting force at their tip was noticeable, with an average value of 8.9 x 10^{-2} MPa for the stress and 12.9 x 10^{-2} N for the resulting force in all models. The stress in the capsular bag, had a slight decrease of maximum values 3.72 x 10^{-2} MPa in the first model and 3.31 x 10^{-2} MPa in the last. But overall, the average value of stress in the capsular bag increased 3.5 times from the model with no traction force to the one with a traction force of 0.15 N. The stress in the IOL and radial displacement had the greatest change, with the maximum stress, of 1.5 x 10^{-1} MPa, in the IOL of *M20* being more than three times the maximum stress, equal to 4.4 x 10^{-2} MPa, in *M2.*

Table 3.3. Maximum values of von Mises stresses in the zonular fibers, capsular bag and crystalline/IOL, as well as radial displacement and resulting force at the tip of the zonular fibers for models M2, M8, M14 and M20.

Model	Variables	Maximum	Average Value
M2	S_Z (MPa)	9.7 x 10^{-2}	8.9 x 10^{-2}
	S_{CB} (MPa)	3.7 x 10^{-2}	1.9 x 10^{-3}
	S_{IOL} (MPa)	4.4 x 10^{-2}	5.8 x 10^{-3}
	δ_r (mm)	-	7.3 x 10^{-3}
	RF_Z (N)	-	12.8 x 10^{-2}
M8	S_Z (MPa)	9.8 x 10^{-2}	8.9 x 10^{-2}
	S_{CB} (MPa)	2.6 x 10^{-2}	4.0 x 10^{-3}
	S_{IOL} (MPa)	6.8 x 10^{-2}	7.7 x 10^{-3}
	δ_r (mm)	-	4.2 x 10^{-3}
	RF_Z (N)	-	12.9 x 10^{-2}
M14	S_Z (MPa)	9.8 x 10^{-2}	8.9 x 10^{-2}
	S_{CB} (MPa)	4.6 x 10^{-2}	6.0 x 10^{-3}
	S_{IOL} (MPa)	1.3 x 10^{-1}	1.2 x 10^{-2}
	δ_r (mm)	-	3.2 x 10^{-3}
	RF_Z (N)	-	12.9 x 10^{-2}
M20	S_Z (MPa)	9.8 x 10^{-2}	8.9 x 10^{-2}
	S_{CB} (MPa)	3.3 x 10^{-2}	6.7 x 10^{-3}
	S_{IOL} (MPa)	1.5 x 10^{-1}	1.4 x 10^{-2}
	δ_r (mm)	-	2.8 x 10^{-3}
	RF_Z (N)	-	12.9 x 10^{-2}

The radial displacement, 7.3 x 10^{-3} mm, in *M2* was almost three times higher than the one in *M20*, 2.8 x 10^{-3} mm. It was also interesting to observe a change of maximum stress in all the model, i.e., for the models with traction forces below RF_X the local maximum stress was located in the zonules, whereas for the models with traction forces greater than this value it was located in the IOL, at the contact point with the edge of the capsulorhexis. These local maximums are highlighted in Figure 3.1. The only exceptions were models *M17*, *M18*, *M23* and *M24* where the local maximum was in the capsular bag, at the edge of the CCC.

Influence of the Diameter of the Capsulorhexis

In this subsection, models *M2* and *M5* will be compared, as well as models *M8* and *M11*. The first two had the same IOL material (hydrophilic acrylic) and the same traction force equal to zero but differed in the size of the capsulorhexis. The other two models had the same material properties but had a traction force applied at the opening of the capsulorhexis of 0.07 N. Models *M2* and *M8* had a small capsulorhexis with a 4 mm diameter and models *M5* and *M11* had a large one, with a 4.5 mm diameter.

With no traction force applied, the distributions and values of stress in the zonules were the same in both models, with average values of 8.9 x 10^{-2} MPa. For the stress in the capsular bag and in the IOL, the maximum values of stress remained the same with the increase of diameter of the capsulorhexis, with the average value of stress in the capsule increasing slightly in the order of 16%, whereas the average value of stress in the IOL remained the same. The radial displacement was almost the same, with 7.3 x 10^{-3} mm and 7.2 x 10^{-3} mm, for *M2* and *M5*, respectively, with only a variance in the order of 1%. The resulting force in both models were also very similar, with a

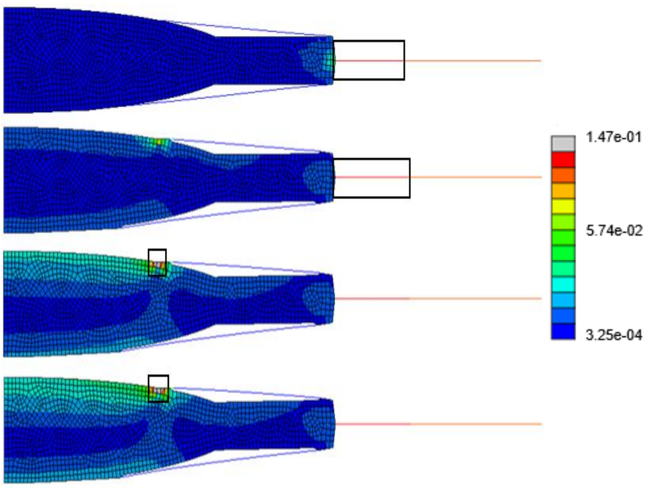

Figure 3.1. Von Mises stresses in all the components of the four models, after cataract surgery with a 4 mm CCC and a hydrophilic acrylic IOL, following ciliary body relaxation: (A) model M2, (B) model M8, (C) model M14 and (D) model M20. The local maximum stresses are highlighted in the black boxes.

variance of 0.7%, that could be neglected. All the results for both models are shown in Table 3.4.

Table 3.4. Maximum values of von Mises stresses in the zonular fibers, capsular bag and IOL, as well as radial displacement and resulting force at the tip of the zonular fibers for the models M2 and M5.

Model	Variables	Maximum	Average Value
M2	S_Z (MPa)	9.7×10^{-2}	8.9×10^{-2}
	S_{CB} (MPa)	3.7×10^{-2}	1.9×10^{-3}
	S_{IOL} (MPa)	4.4×10^{-2}	5.8×10^{-3}
	δ_r (mm)	-	7.3×10^{-3}
	RF_Z (N)	-	12.8×10^{-2}
M5	S_Z (MPa)	9.7×10^{-2}	8.9×10^{-2}
	S_{CB} (MPa)	3.7×10^{-2}	2.2×10^{-3}
	S_{IOL} (MPa)	4.4×10^{-2}	5.8×10^{-3}
	δ_r (mm)	-	7.2×10^{-3}
	RF_Z (N)	-	12.9×10^{-2}

In this subsection, there was a need to perform another outcomes analysis, since with traction force in the opening of the capsulorhexis, the values between the same models with different Φ_{ccc} changed more than with no traction force.

The stress in the zonules was still the same, with an average value of 8.9×10^{-2} MPa for both models. The values are all displayed in Table 3.5. The average and maximum value of stress in the IOL decreased with the increase of the diameter of the capsulorhexis, with average values of 7.7×10^{-3} MPa and of 7.4×10^{-2} MPa and maximum values of 6.8×10^{-2} MPa and 5.2×10^{-2} MPa, for models *M8* and *M11*, respectively. The decrease in average values of stress was in the order of the 4%, whereas in the maximum stress it was 31%. The stresses in the IOL are shown in Figure 3.2, where even though model *M8* has a higher local stress in the point where the traction force is applied, model *M11* showed higher values of stress in the haptic, near the insertion point of the

Table 3.5. Maximum values of von Mises stresses in the zonular fibers, capsular bag and IOL, as well as radial displacement and resulting force at the tip of the zonular fibers for the models M8 and M11.

Model	Variables	Maximum	Average Value
M8	S_Z (MPa)	9.8×10^{-2}	8.9×10^{-2}
	S_{CB} (MPa)	2.6×10^{-2}	4.0×10^{-3}
	S_{IOL} (MPa)	6.8×10^{-2}	7.7×10^{-3}
	δ_r (mm)	4.2×10^{-3}	-
	RF_Z (N)	12.9×10^{-2}	-
M11	S_Z (MPa)	9.8×10^{-2}	8.9×10^{-2}
	S_{CB} (MPa)	7.8×10^{-2}	4.2×10^{-3}
	S_{IOL} (MPa)	5.2×10^{-2}	7.4×10^{-3}
	δ_r (mm)	5.9×10^{-3}	-
	RF_Z (N)	12.9×10^{-2}	-

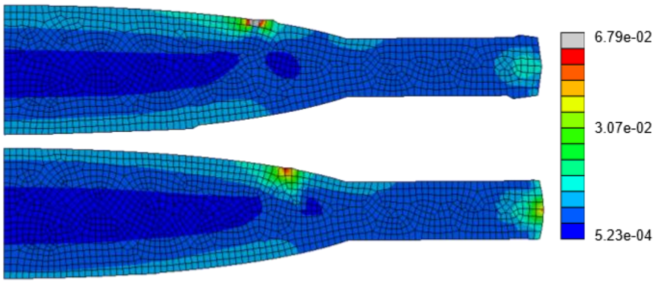

Figure 3.2. Von Mises stresses in the hydrophilic acrylic IOL (in MPa), for the two models, after cataract surgery and a traction force of 0.07N, following ciliary body relaxation: (A) model M8, (B) model M11.

zonule. In the capsular bag, the maximum stress value computed for model *M11,* 7.8×10^{-2} MPa, was three times higher than the one computed for model *M8*, 2.6×10^{-2} MPa, but had slight increase of 5% of average values from the model with the smaller CCC to the one with the larger CCC. Whereas the resulting force at the tip of the zonules remained constant with a value of 12.9×10^{-2} N, the radial displacement was almost 1.5 times higher in model *M11* than in model *M8*, with values of 5.9×10^{-3} mm to 4.2×10^{-3} mm, respectively.

Maximum stress

Another important aspect to assess was the maximum values of stress in each of the models. For all the models, when the traction force was lower than their respective RF_X, the maximum stress was in the zonules, near their insertion point in the capsular bag. For all the models with small capsulorhexis and the models with PMMA material and a large capsulorhexis, when the traction force became equal or higher than RF_X, the maximum value of stress laid in the IOL near the node where the traction force was applied. For the models with large capsulorhexis, made of hydrophilic or hydrophobic acrylic and with a traction force equal or higher than RF_X, the maximum stress was in the capsular bag. The dashed line in the figures represents the value of RF_X.

Summary

All parameters tested showed they had some influence on the overall model. In summary, with the increase of the traction force and of the stiffness of the materials, i.e., their Young's modulus, the stress in the zonules and in the IOL would increase, as well as the resulting force at the tip of the zonules, whereas the stress in the capsular bag and the radial displacement would decrease. With the increase of the diameter of the capsulorhexis, and the traction force equal to zero, the overall stress in the models would not change, while the radial displacement would decrease and the resulting force increase, but so very slightly they were not considered as significant. Finally, with the increase of the diameter of the capsulorhexis, with the traction force greater than zero, all the parameters studied would have a contrary behavior than the ones described earlier, i.e., the stress in the zonules and in the IOL decreased, as well as the resulting force at the tip of the zonules, whereas the stress in the capsular bag and the radial displacement increased.

It was also important to notice that across all models of pseudophakic eyes, the part that would undergo less change were the zonules, where no parameter seemed to influence greatly their maximum and average values of stress nor the resulting forces computed at their tips. The maximum variation between the average values of stress was of 1% and between the resulting force was 0.8%.

4. Discussion

The complete eye before surgery that was modelled by an axisymmetrical model in this work yielded very similar results compared to previous studies, of maximum and distribution of stresses, as well as of resulting forces in the zonules and displacement in the radial direction and in lens thickness. Even though simplifications were made in the properties of materials, i.e., considering all the materials as linearly elastic isotropic, and in the geometry of the crystalline, the presented model could be validated. It was also demonstrated that a model with a shell capsular bag instead of a membrane one yielded very similar outcomes and could also be used in the modulation of the crystalline under cataract surgery.

Comparing the human crystalline complex with a pseudophakic eye, a decrease of stress in the capsular bag and of radial displacement of the new complex was observed, with a consequent increase of resulting force and stress in the zonules, as well as an increase in stress in the IOL. These outcomes could be compared with the influence of the stiffness of the IOL material through the pseudophakic models, since the biggest difference in the eye after surgery, is the difference in stiffness of the human crystalline compared with the stiffness of all the synthetic IOL materials. The IOLs were at least a thousand times stiffer than any component of the crystalline, making them support more stress than the crystalline and consequently relieve the stress in the capsular bag. With all the models undergoing the same displacement of 0.5 mm at the tip of the zonules, the stiff IOLs lead to the zonules having to stretch more to pull the lens and the capsular bag, and consequently putting the zonular fibers in a higher state of stress, with its maximum at the intersection node of the three parts of the model. On one hand, the IOLs gave more support to minimize stress in the capsule and eventually decrease its risk of rupture, but on the other hand it put the zonules into a state of more stress with a higher possibility for them to break and lead to an IOL-capsular bag dislocation. Ideally, to avoid this post-operative complication, a lens with a stiffness closer to the one of the human crystalline would be the best solution to try and maintain the state of stress of the capsular bag and the zonules closer to their original state.

Comparing only pseudophakic eyes, knowing that the stiffer PMMA IOL was at least 500 times stiffer than the acrylic lenses, a slight increase of 5% in average stress of the IOL can be considered negligible. The biggest changes observed while increasing the stiffness of the IOLs was a big decrease in average capsular stress and in radial displacement. This outcome is comparable with the case studied before, i.e., the substitution of the crystalline with any IOL, where an increase in IOL stiffness would give more support to the capsular bag and minimize its average stress. In the zonules, no change in maximum and average values of stress was observed, nor change in the resulting force at their tip.

The increase of the traction force at the opening of the capsulorhexis showed a big influence in the distribution of stress in all the model, increasing the stress in the IOL (principally in its optic) and decreasing the radial displacement, substantially. Even without knowing the *in vivo* values of the traction force at the edge of the capsulorhexis, it was relevant to study it to understand if the models built in this work were sensible to its variation. As it was shown previously, the stress in the IOL and the capsular bag (for acrylic lenses with a large capsulorhexis) were very sensible to this variation changing the maximum values of stress from the zonules to either the capsular bag or the IOL. It was expected to observe an increase in average stress in the capsular bag and in the IOL, since these two parts were subjected to an increasing load in the opposite direction from that of the ciliary body relaxation. Furthermore, Hudish et al. stated that with fibrosis on the edge of the capsulotomy, leading to ACCS, the apparition of a centripetal force towards the center of its opening, greater than the force exerted by the zonules, could lead to the rupture of the zonular fibers and cause late IOL-capsular bag dislocation (Hudish et al., 2017). But in this work, it was shown that an increase of this centripetal force, i.e., the traction force that was applied, did not influence the average stress in the zonules, even when it was higher than the resulting force in the zonules.

A small and large capsulorhexis, with 72.73% and 82.83% of the diameter of the IOL optic, with no traction force applied at the edge of the capsulorhexis were compared and did not seem to have a direct impact on the stresses in two parts of the model. Only the capsular bag seemed to have a slight increase of 16% in its average stress, with the increasing diameter of the CCC. Since it was known that the size of the capsulorhexis had an impact on some post-surgery complications (Langwińska-Wośko et al., 2011), the outcomes found did not seem realistic. That was why the decision to simulate the traction force at the edge of the capsulorhexis was made, even without knowing the *in vivo* values of this force. Even though the stress of all the parameters, the radial displacement and the resulting force seemed to be more sensible to changes in diameter than without traction force, the variation in the stress of the zonules was not considerable. With a larger capsulorhexis, it was shown that the distribution and values of stress in the haptic of the IOL and in the capsular were higher than with a small one. These results not only confirmed how important it was to model the traction forces, since they influenced all the parts the model, but lead us to understand that with a smaller capsulorhexis it was possible to relieve the stress in the capsular bag and eventually avoid its rupture, with a consequent IOL dislocation. This outcome seemed to be contrary to the one given by Gimbel et al. (2005) that stated that a smaller capsulorhexis lead to a higher probability of incidence of IOL-capsular bag dislocation, because it developed more ACCS than a large capsulorhexis. In this work, it was assumed that both large and small capsulorhexis had suffered ACCS and that the resulting traction force on its edge was the same in both cases. For that same traction force, the smaller capsulorhexis seemed more favorable in giving support to the capsular bag.

In summary, after surgery the stress in the zonules almost doubled in every model whereas in the capsular bag it decreased greatly in almost every model (except for models with hydrophilic or a hydrophobic acrylic lens, a large capsulorhexis and a traction force higher than their respective RF_X, i.e., *M17*, *M18*, *M23* and *M24*), due to the increased stiffness in any IOL compared with the crystalline. The fact that the IOLs had a stiffness at least a thousand times higher than the human crystalline lead to the IOLs giving a bigger support to the capsular bag, relieving it of stress. No parameter studied lowered the general state of stress in the zonules post-surgery. The simplified geometry of the natural human crystalline lens model, that could have an impact on the distribution of stress in the capsular bag, did not seem to influence the outcomes of the pseudophakic eye models, since after surgery the capsule had a completely different shape, and shrank itself to the IOL.

5. Conclusion

Even though a few simplifications were made during the construction of the complete crystalline, such as a simplified geometry with a perfect ellipsoid shape for the crystalline lens and linear isotropic materials, the models with a membrane capsular bag and a shell capsular bag could both be compared with previous numerical models and proved to be capable of replicating the process of disaccommodation, validating the choices made during this work.

In this work, a human crystalline lens and its associated structures, i.e., the capsular bag and the zonular fibers, and pseudophakic eyes with a one-piece IOL were built in a FE model. All the models were built based on axisymmetric elements, with linearly elastic isotropic materials, based on the fact that the crystalline lens was a perfectly symmetric structure, around its optical axis. A radial displacement was applied at the tip of the zonular fibers to mimic the movement of the ciliary body during the process of disaccommodation. As there is very few in vivo information about all the materials properties, the major part of this work was based on in silico studies, about the complete crystalline complex.

In the pseudophakic eye models, the increase of force and stress in the zonules could in fact explain why years after surgery some zonules would break leading to an IOL-capsular bag complex dislocation. This assumption could not be simulated, since there was no information about the tensile strength of the zonules. No variation of parameters in the pseudophakic models, i.e., increase of the Young's moduli of the IOLs, different diameters of capsulorhexis and increased traction force, seemed to have a significant impact on the zonules. It was important to verify their impact on the zonules, since their rupture is the main precursor of IOL-capsular bag dislocation. Since no changes were observed, it was possible to speculate about saying that an axisymmetric model of the pseudophakic eye could be too simplified and that a more realistic geometry of an IOL could have a greater influence on the outcomes of the simulations. More information about the tensile strength of the zonular fibers and the capsular bag would also be crucial to better understand at what point they would break and lead to an IOL dislocation. When studying the influence of the diameter of the capsulorhexis when no traction force was applied at its edge, no change in the stresses of the model proved how important it was to model this traction force and to have in vivo information about it, to help building more realistic models.

Some limitations exist in the field, such as few information about all the in vivo mechanical properties of all the components of the human lens complex and the real values of traction force exerted in the opening of the capsulorhexis, and it is of extreme importance that new in vivo data becomes available in order to further study cataract surgery, its post-operative complication and to find new solutions to avoid them.

Since this work presented an axisymmetric model, the IOLs built were simplified to represent perfectly axisymmetric lenses, which is not the real configuration of the lens. The geometry of the IOLs could be improved in future works, thanks to 3D models that could replicate different types of asymmetric IOLs (one-piece, three-piece or plate IOLs), in a more realistic way. Moreover, additional parameters could be studied to understand their influence in the overall stresses in all the parts of the models, such as the influence of the gravity, the positioning of the IOL, the type of capsulotomy performed and different densities of zonules (to mimic zonular dehiscence). *In vivo* values of the tensile strength of the zonules and the capsular bag would also have a great impact on the models, since it would be possible to replicate more realistic behaviors in these materials and to know when they would tear.

Regardless of these limitations, no modelling of the eye under cataract surgery like the one proposed here was found in the literature, turning this work into a complement of the already existing studies about the crystalline complex.

References

Al-Halafi, A. M., Al-Harthi, E., Al-Amro, S., & El-Asrar, A. A. (2011). Visual outcome and complications of pars plana vitrectomy for dislocated intraocular lenses. *Saudi Journal of Ophthalmology*, *25*(2), 187–192. https://doi.org/10.1016/j.sjopt.2011.01.013

Ascaso, F. J., & Huerv, V. (2013). The History of Cataract Surgery. In *Cataract Surgery*. InTech. https://doi.org/10.5772/19243

Bassnett, S., Missey, H., & Vucemilo, I. (1999). Molecular architecture of the lens fiber cell basal membrane complex. *Journal of Cell Science*, *112 (Pt 1*, 2155–2165.

Bozukova, D., Werner, L., Mamalis, N., Gobin, L., Pagnoulle, C., Floyd, A., … Morris, C. (2015). Double-C loop platform in combination with hydrophobic and hydrophilic acrylic intraocular lens materials. *Journal of Cataract and Refractive Surgery*, *41*(7), 1490–1502. https://doi.org/10.1016/j.jcrs.2014.10.042

Burd, H. J., Judge, S. J., & Cross, J. A. (2002). Numerical modelling of the accommodating lens. *Vision Research*, *42*(18), 2235–2251. https://doi.org/10.1016/S0042-6989(02)00094-9

Cataracts. (2010). *National Eye Institute*. Retrieved from https://www.nei.nih.gov/eyedata/cataract#5

Fisher, R., & Pettet, B. (1972). The postnatal growth of the capsule of the human crystalline lens. *Journal of Anatomy*, *112*, 207–214.

Gimbel, H. V., Condon, G. P., Kohnen, T., Olson, R. J., & Halkiadakis, I. (2005). Late in-the-bag intraocular lens dislocation: Incidence, prevention, and management. *Journal of Cataract and Refractive Surgery*, *31*(11), 2193–2204. https://doi.org/10.1016/j.jcrs.2005.06.053

Goldberg, D. B. (2011). Computer-animated model of accommodation and theory of reciprocal zonular action. *Clinical Ophthalmology*, *5*(1), 1559–1566. https://doi.org/10.2147/OPTH.S25983

Hudish, T., Helm, M. L., Patel, A. S., Feldman, B. H., & DelMonte, D. W. (2017). *Anterior Capsular Contraction Syndrome*. Retrieved from http://eyewiki.aao.org/Anterior_Capsular_Contraction_Syndrome

Lanchares, E., Navarro, R., & Calvo, B. (2012). Hyperelastic modelling of the crystalline lens: Accommodation and presbyopia. *Journal of Optometry*, *5*(3), 110–120. https://doi.org/10.1016/j.optom.2012.05.006

Langwińska-Wośko, E., Broniek-Kowalik, K., & Szulborski, K. (2011). The impact of capsulorhexis diameter, localization and shape on posterior capsule opacification. *Medical Science Monitor : International Medical Journal of Experimental and Clinical Research*, *17*(10), CR577-82. https://doi.org/10.12659/MSM.881984

Liu, X., Wang, L., Du, C., Li, D., & Fan, Y. (2015). Mechanism of lens capsular rupture following blunt trauma: a finite element study. *Computer Methods in Biomechanics and Biomedical Engineering*, *18*(8), 914–921. https://doi.org/10.1080/10255842.2014.975798

Prokofyeva, E., Wegener, A., & Zrenner, E. (2013). Cataract prevalence and prevention in Europe: A literature review. *Acta Ophthalmologica*, *91*(5), 395–405. https://doi.org/10.1111/j.1755-3768.2012.02444.x

Schachar, R. A. (1992). Cause and treatment of presbyopia with a method for increasing the amplitude of accommodation. *Annals of Ophthalmology*, *24*(12), 445–447, 452. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1485739

Sheehan, M. T., Goncharov, A., & Dainty, J. C. (2012). *Eye modelling for personalised intraocular lens design*. https://doi.org/Sheehan2012

Southall, J. P. C. (1962). *Helmholtz's Treatise on Physiological Optics (Volume 3)*. Dover Publications.

van Alphen, G. W. H. M., & Graebel, W. P. (1991). Elasticity of tissues involved in accommodation. *Vision Research*, *31*(7–8), 1417–1438. https://doi.org/10.1016/0042-6989(91)90061-9

Wang, K., Venetsanos, D. T., Wang, J., Augousti, A. T., & Pierscionek, B. K. (2017). The importance of parameter choice in modelling dynamics of the eye lens article. *Scientific Reports*, *7*(1), 1–12. https://doi.org/10.1038/s41598-017-16854-9

Weeber, H. A., & van der Heijde, R. G. L. (2008). Internal deformation of the human crystalline lens during accommodation. *Acta Ophthalmologica*, *86*(6), 642–647. https://doi.org/10.1111/j.1600-0420.2007.01116.x