3D Biomechanical modelling of the human lens complex under cataract surgery

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Abstract

The crystalline lens is a transparent structure responsible to focus and maintain a clear image on the retina. Currently, when the lens become clouded, condition termed cataract, the removal of crystalline lens with the replacement by an Intraocular lens (IOL) is the most applied cataract treatment. The eye is denominated a pseudophakic eye. After some years, several complications can occur namely the late in-the-bag IOL dislocation. Although rare, with the ageing population, this dislocation may become a common complication in the future. Recent studies reported Pseudoexfoliation syndrome (PES) in 40% of the cases, being therefore the most common risk factor known. This disease is characterized by deposition of fibrillar material in the capsule, which can lead to progressive zonular weakening. The work aims to investigate the possible biomechanical causes of the complication under study in the lens complex through the development of 3D Finite element (FE) models. In the several models, it is considered the influence of the material properties of the IOL, its positioning within the capsule, the gravity and the zonular thickness. The outcomes raised attention for the IOL material choice, since this parameter has a very high influence in the eye biomechanical behavior. Regarding the pathology under study, there is evidence that the zonular weakening influences the results found on the zonules and, therefore, there is a great probability of this leads to the late in-the-bag IOL dislocation occurs with zonular weakening. *In vivo* and *in vitro* studies are a need, particularly of the pseudophakic eye.
Keywords: Post Cataract Surgery; Pseudoexfoliation syndrome; late in-the-bag IOL dislocation; 3D Finite element model.

1. Introduction

In 2015, approximately 20 millions of cataract extractions was performed around the world [1]. Between that year and 2030, the number of people aged 60 years and over is expected to increase from 901 to 1.4 billion and therefore, the number of cataract diagnosis people is expected to triple [2]. Moreover, the development of surgical cataract technologies, the improvement in the quality and safety of surgical techniques and the good functional results lead to increase the surgery frequency at earlier age [3]. In these cases, the IOL will stay in the eye for a longer period which increases the probability of late complications. For example, regarding the late in-the-bag IOL dislocation which is one of the most serious issues of the cataract surgery, a study referred that the cumulative risk at 5 and 25 years after cataract surgery was 0.1% and 1.7%, respectively [4]. Therefore, a complication which is considered almost rare currently, may become a common complication in the future. There are several risk factors related to late in-the-bag IOL dislocation, being the most common the Pseudoexfoliation syndrome (PES) [5]. PES affects around 70 million people in the world [6] and it is likely to produce progressive zonular dehiscence which may lead to late in-the-bag dislocation. Also the IOL material and positioning as well as the gravity load may have influence on the lens complex behavior and they may be the cause of the mentioned late dislocation.

The previous numbers highlight the need of studying the lens complex before and after cataract surgery. Since the mentioned complication is caused by changes in the lens complex at several levels, in particular, at the biomechanical level, the approach of the problem through FE method is very relevant. The FE modelling allows the modelling of the several structures in both, material properties and structural geometry and, consequently, it allows to obtain reasonable outcomes of the mechanical behavior of the lens complex.

The main goal of the present dissertation is to investigate possible biomechanical causes of the complication under study in the lens complex. To achieve this goal it was followed the following two steps:

1. To construct a 3D computational model of the intact human lens complex and a 3D computational model of the lens complex under cataract surgery through the previous intact model;

2. To simulate certain conditions under which the lens complex, inclusive the zonules, may be subjected before and after cataract surgery. The goal is to know their impact on the late in-the-bag IOL dislocation.

2. Background

2.1. Anatomy

The human eye is one of the most important sensory organ and the crystalline lens is part of the anterior segment of its structure. The crystalline lens is a transparent structure located behind the iris, as illustrated in Fig.1. This structure consists of a dense substance of packed cells and fibers divided in two shells. A thicker containing the youngest cells - cortex - and a central portion composed by older cells, known as nucleus. Enclosing the entire lens, there is a capsule of roughly 10um which works as a barrier to the exterior. During accommodation process, this elastic membrane molds the shape of lens in response to the zonular fibers tension. The lens is suspended by these zonular fibers that surround the lens and attach it to the ciliary body, the muscle. The zonules are part of a fibrous system and this fibrous rigging confers support to the lens and capsule. Despite the zonular insertion be done in the equatorial region of the lens, authors describe the existence of three distinct sets of zonules: an anterior, an equatorial and a posterior [7]. The lens has an oblate spheroid shape with a diameter varying between 6.5 and 10mm throughout life and with a maximum thickness of 5mm. Along with the cornea, the lens is an optical component of the eye, responsible to focus and maintain a clear image on the retina.

2.2. Accommodation process

The crystalline lens is a crucial component in the optical power adjustment of the human eye. Through zonules, the ciliary body induces changes in lens shape and, consequently, in its refractive power due to an alteration in the lens curvature. By increasing the lens curvature, it is possible to focus the closer objects and this process of lens adjustment is called accommodation. The reverse process is termed disaccommodation and allows to view distant objects.

For centuries, theories about accommodation mechanism have been formulated however the greatest consensus is still achieved by the classical Helmholtz theory. According to Helmholtz's mechanism, the unaccommodated lens has a flattened shape since the zonular fibers are in a radial tension state while the ciliary muscle is relaxed. On the other hand, the ciliary body contraction conducts to a reduction of zonular tension and, as result, the lens substance become more convex, natural curvature (accommodated state). Conversely to Helmholtz's, the Schachar's theory defends that the rounder shape of the accommodated state is a result of an increase of zonular tension.

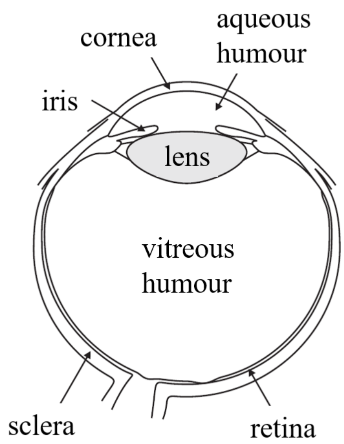

Figure 1: The principal components of the human eye. Superior view of the human eye. Adapted from [8].

2.3. Cataract surgery

The procedure of cataract extraction starts with an incision in the cornea. Through this incision, the surgery instruments are inserted and via a Continuous Curvilinear Capsulorrhexis (CCC) of 4-5mm in the capsular bag it is possible to access the cataract. Using ultrasonic energy, the lens nucleus and cortex are divided into very small pieces which, later, are aspirated via vacuum forces. Before the insertion of the IOL into the eye, a viscoelastic substance is injected within the capsule in order to create space and ensure the minimal impact on the zonular fibers. It largely contributes to minimize the complications and risks of cataract extractions. Shortly after the removal of the substance, the capsular bag collapses and seals itself to the implanted IOL.

Additionally to innovated surgical techniques, another important point is the progressive development of IOL designs and biomaterials. To please both surgeons and patients, the ideal IOL has to be easy to implant, minimizing the intraoperative complications and, simultaneously, it has to have a good optical performance and lasting vision. A characteristic IOL is composed of two parts: the optic, the actual lens, and the haptics, the side structures which maintain the IOL in position within the capsular bag. Within rigid materials, the Polymethylmethacrylate (PMMA) is the most bio compatible however the corneal incision required to implant this type of IOL is larger than the one require by a foldable IOL. Moreover, those composed by foldable material tend to be more robust and to experience less post-surgery dislocations [9]. The foldable biomaterials are divided in two major groups: acrylic and silicone. Despite these IOL materials present advantages and disadvantages, the acrylic lenses are the most used today, as it often has a best corrected visual acuity than silicone lens [10]. Furthermore, a key aspect to take into consideration is the mechanical behavior of the IOLs. With the purpose of IOL perfectly fitting the capsular bag, the lens must be compressible and, after insertion on the eye, must have shape memory [11]. These advances allow to build models for specific purposes and to prevent some complications.

2.3.1 Post-surgery Complications

When the IOL is implanted, the propose is that the artificial lens remains into the eye without complications throughout life. Unfortunately, the theoretical concept does not pan out in that way in real life and after few years problems may occur namely the late in-the-bag IOL dislocation. Although rare, it is a potentially serious complication.

Nowadays, the results of the cataract technique evolution are clear, surgical complications are only reported in 2,09% of the cases [12], however, the late IOL in-the-bag dislocation is still a stated complication. This dislocation occurs when the IOL - capsular bag complex suffers a dislocation. The most common dislocation is the inferior, in which the superior zonular fibers suffer rupture and the inferior zonules suspend the capsular bag as represented in the Fig.2. Taking into account the direction of the displacement, it is possible to suppose that gravity force and the IOL positioning can have impact in this late complication.

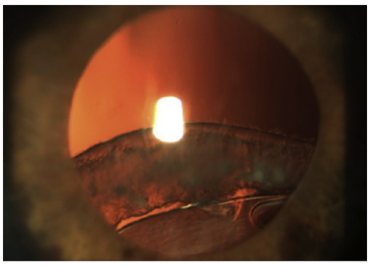

Figure 2: Late in-the-bag IOL dislocation. Adapted from [13].

In the last years the cataract surgery has boomed in younger people, raising questions about the long-term impact of IOL implantation, namely in late post-surgical complications [5]. It assumes a crucial role to know the risk factors of this complication. Several studies reported PES as the most common risk factor, contributing to more than 40% of the IOL displacements [5, 13]. PES is a disease characterized by production and deposition of fibrillar material in several tissues. This pathology complicates the pupil dilation, increased inflammatory response and it leads to progressive zonular fibers weakening. Thus, the monitoring of ocular structures, especially capsular bag and zonules health can assume an important role to prevent possible complications, namely the late IOL in-the-bag dislocation.

3. Implementation

A first step in developing a 3D FE model of the human lens complex under cataract surgery is the development of a valid model of the intact human crystalline lens. The results of an axisymmetric model and of a 3D-model with an axisymmetric geometry are analogous, reason why the FE models found on literature are almost all 2D axisymmetric. Although that, since the IOL has a non symmetrical geometry, the 3D approach of the model of lens complex under cataract surgery becomes relevant.

3.1. Lens geometry

The intact eye model contains the following anatomical parts of the eye: lens cortex, lens nucleus, capsular bag and the zonules. These last structures are conventionally divided into anterior, central and posterior shells. One of the tips of these shells are linked to the capsular bag in the anterior, equatorial and posterior parts, respectively, while the other tip is linked to the ciliary muscle through a single attaching point. The representation of the three shells is essential since the anterior and posterior shells have a great impact in the lens shape change during accommodation.

The modelling of the structures was made by ABAQUS (Dassault Systèmes Simulia Corp., USA) and the cross-section of them is described in Fig.3. The first model geometry is based on a fully accommodated state, in accordance with the theory of Von Helmholtz, and it is assumed that the force of the zonules acting on the crystalline is negligible. In contrast, the disaccommodated state is achieved through the application of a displacement on the zonules, simulating the ciliary muscle action.

The lens nucleus and the lens cortex are shaped as homogeneous solids while the lens capsule is defined as a membrane around the lens. This membrane is modelled with uniform thickness although to the inexistence of consensus about this topic. Also with constant thickness, the zonules fibers are modelled as a shell. To study the relationship between the deformation and the displacement during accommodation process the following parameters were computed: Total radius, R_T, Lens radius, R_L, Nucleus radius, R_N, Lens thickness, T_L, Nucleus thickness,

T_N, Capsule thickness, T_C and Zonule thickness, T_Z. The accommodated geometry parameters that were taken corresponded to a 29 years old person and its dimensions and sources are presented in Table 1.

The pseudophakic eye model is constituted of IOL, an homogeneous solid, capsular bag and zonules. After cataract surgery, when the IOL is placed within capsular bag, the capsule sealed itself to the IOL and, consequently, the distance between the shells of zonules also decreases. In the present geometry model, the capsule goes along the geometry of the IOL with 0.96mm of thickness, remaining its ellipsoidal geometry (Fig. 5). The parameters of the pseudophakic eye geometry computed were Optic radius, R_O, Optic thickness, T_O, Haptic thickness T_H, CCC radius R_{CCC} and they are depicted in the Table 1 and represented in the Fig. 4 and 5. During surgery, in the capsular bag is done a CCC with a variable diameter. Langwinska et al., decided to study the influence of CCC size in several post-surgery complications. Based on the results of this research, 72% of the IOL optic diameter was chosen as the ideal CCC size.

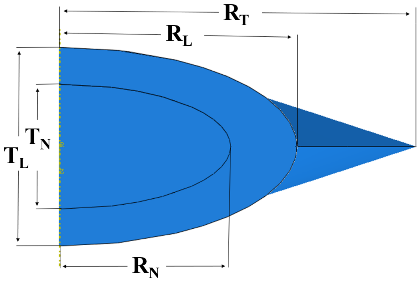

Figure 3: Geometrical parameters of the 3D intact human lens model profile in a fully accommodated state.

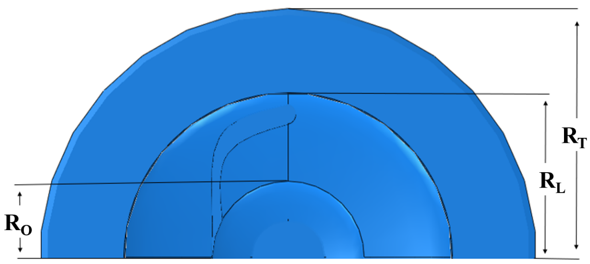

Figure 4: Geometrical parameters of the 3D-model after cataract surgery. Frontal section.

3.2. Material properties

Even though the lens substance and the capsule do not have a evident arrangement of its fibers, they are modelled as linear elastic materials, being its mechanical properties and sources described

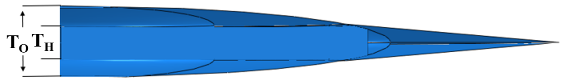

Figure 5: Geometrical parameters of the 3D-model profile after cataract surgery. Sagital section.

in the Table 2. In contrast to what was done in the FE models until now, the mechanical properties of the zonular fibers are considered hyperelastic anisotropic. The fibers have an important role keeping the crystalline lens in position and, for this reason, to understand its mechanical behavior is essential. Thus, to model the material behavior of the zonules, it was used the anisotropic hyperelastic constitutive model proposed by Holzapfel-Gasser-Ogden (HGO) [19]. This model has been largely used to model collagen fiber-reinforced biological materials.

For an hyperelastic anisotropic material defined by the HGO model, ABAQUS® requires five parameters to be assigned to the material: C_{10}, D_1, k_1, k_2 and *kappa*. The C_{10} and D_1 express the stiffness and compressibility of the matrix of the material and they are defined as a non-linear hyperelastic neo-Hookean isotropic model. These parameters were obtained from Young's modulus, E, Poisson's Ratio, ν and Bulk modulus, K by the following expressions. The remaining parameters are related to the fibers behavior, k_1 influences the stiffness of fibers and has dimension of stress, k_2 is related to non-linearity of the fiber behavior and *kappa* defines the orientation of the fibers. The last parameter varies between 0 for completely aligned fibers, and 1/3 for fibers with a random orientation.

In order to achieve the most appropriate fibers parameters it was performed an initial analysis to optimize and validate the intact model mechanical properties. The values that best fit the expected results are presented in Table 2.

Table 1: Geometric data of lens complex, zonules, IOLs.

Dimension	Value (mm)	Source
Total radius, R_T	6.5	[14]
Lens radius, R_L	4.3	[14]
Nucleus radius, R_N	3.1	[15]
Lens thickness, T_L	3.6	[15]
Nucleus thickness, T_N	2.26	[15]
Capsule thickness, T_C	0.01	[16]
Zonule thickness, T_Z	0.01	[17]
Optic radius, R_O	2	[11]
Optic thickness, T_O	0.96	[11]
Haptic thickness, T_H	0.44	[11]
CCC radius, R_{CCC}	1.44	[18]

To construct the pseudophakic eye model, the IOL is defined as a linear elastic material and the several parameters of the IOL materials used are represented in the Table 2.

3.3. Boundary and loading conditions and interactions

All the structures are interacting through a tie, ensuring no relative movement occurs between the components. In light of that, to guarantee that zonular fibers were anchored on the capsular bag, a tie between these components was applied. According to Besnett et al., it was also considered the master-slave approach between the lens capsule and the lens cortex because the author argues the existence of an attachment capable to strongly resist the accommodation process [24].

To simulate the accommodation process in accordance with Helmholtz theory, it was applied a displacement of 0.5mm on each zonule tip. This displacement represents the expected amplitude of movement of the ciliary body, which had a maximal change in diameter between 1 and 1.2mm [20]. To establish the boundary conditions, some assumptions were made. The superior and inferior pole of nucleus and cortex was fixed, being only allowed displacement and rotation in Y-direction. Moreover, it is applied in the zonules a boundary condition, ensuring the zonules motion should only occur in the X-direction and Z-direction. It is generally thought the gravity has influence the lens complex so, it was added a gravity force. For this purpose, the density is an ABAQUS required parameter and the lens density is approximately $1076 kg/m^3$ [25].

The nucleus and cortex were modelled using 10-node quadratic tetrahedral element (C3D10) which is a type of element appropriated in problems with no contact. With the aim of perfectly fitting with the lens cortex, the capsular bag were meshed with 3-node triangular membrane elements (M3D3). Each set of zonules were modelled as a continuous sheet and meshed using 3-node triangular shell element (S3). The total number of elements was 46187 and the total number of nodes was 34924.

When an IOL is implanted the accommodation process starts to be called pseudophakic accommodation. Several studies have shown that, after surgery, this pseudo-accommodation process exists in most of the eyes. Therefore, the displacement of 0.5mm applied in the zonule tip was maintained in this model.

The IOL is fixed in the poles of the optic similarly what happens in the intact eye model and the zonular fibers have the same boundary conditions of the intact model. Additionally, some of the pseudophakic models have the influence of the gravity force. To compute this force, it is required the density of the several IOL materials. The acrylic and silicone density are of $1180 kg/m^3$ and of about $1200 kg/m^3$, respectively [25]. According to Ascaso & Huerv, the capsular bag is completely in contact with the IOL and, so, a tie was considered between these two structures [26].

The IOL was moddeled using 10-node quadratic tetrahedral element (C3D10) and the total number of elements and nodes are 124800 and 148072, respectively. In this model the mesh was refined in

Table 2: Mechanical properties of the lens complex, zonules and IOLs after optimization and validation

	Formulation	Parameters	Source
Cortex	Linear Elastic	$E = 0.0037$ MPa $\nu = 0.47$	[20]
Nucleus	Linear Elastic	$E = 0.0006$ MPa $\nu = 0.47$	
Capsular Bag	Linear Elastic	$E = 1.5$ MPa $\nu = 0.47$	[21]
Zonules	Hyperelastic Anisotropic (Holzapfel)	$C_{10} = 0.0583$ $D_1 = 1.0286$ $k_1 = 0.87$ MPa $k_2 = 21.75$ $kappa = 0.3$	Current work
Hydrophilic Acrylic	Linear Elastic	$E = 3.911$ MPa $\nu = 0.39$	[22]
Hydrophobic Acrylic	Linear Elastic	$E = 5.829$ MPa $\nu = 0.39$	
Silicone	Linear Elastic	$E = 1.9$ MPa $\nu = 0.39$	[23]
Silicone (I)	Linear Elastic	$E = 0.3$ MPa $\nu = 0.39$	

order to obtain a numerical outcome.

3.4. Description of the models

From the intact eye model, the first set of models was created in order to study the influence of few parameters such as gravity and zonular weakening. Those changes in the 3D FE model of the intact eye and the development of an intact eye model was essential, not only because it is the single model which can be validated through literature, but also because this model is important to understand what happens in the eye before surgery. The second set of models has an IOL taking the place of the crystalline lens and in these models were studied the influence of gravity and zonular weakening, the IOL material and positioning. The outcomes of the intact model are important since they can be compared with some results of the pseudophakic model and can contribute to draw better conclusions.

The description of the features of the models described in this work are summed up in Table 3.

4. Results

Before building the post-surgery eye model, several simulations were carried out to optimize and validate the material properties of the zonules and, consequently, the intact eye model.

The *in vivo* and *in vitro* tests performed in the lens complex studied the change of lens thickness and radius during accommodation process. Those variations were used to compare with the numerical calculations of the present study. Regarding resulting force, the value of 0.0945N lies between the interval of values found by Burd et al., 0.08-0.1N [14]. During accommodation, it is observed a decreased of 10.75% of the lens thickness, value very closer to the value found by Lanchares et al. in its in silico simulations and by Dubbleman et al. in its *in vivo* tests [27, 15]. The lens radius expands 6.6% of lens radius which has the same percentage found by Lanchares et al. and it is slightly smaller than the value found by Burd et al. and Weeber et al. [27, 14, 28].

Despite the geometry simplification and the constant thickness of the capsular bag assumed in the present work, through the previous validation, it is possible to conclude that the 3D intact model constructed is adequate.

After validation, for the diverse models, it was measured the S11, which represents the component of normal stress in the U1 direction. The choice of U1 direction was made in accordance with the IOL haptics direction, whose effect is significant in stress.

It is worth mentioning that since there is no biomechanical models in literature of the eye with an IOL implanted, the analysis carried out to the pseudophakic models had to be performed qualitatively. Despite the similarities on the mechanical properties, the geometry of the intact and pseudophakic eye models are different therefore, the biomechanical comparison between models has no meaning. However, taking into account the high stiffness of the IOL when compared with the crystalline lens stiffness, it is reasonable to understand the significant increase of stress in the second set of models, both in IOL and in zonules. The less stiff IOL material tested is at least eighty times stiffer than any crystalline substance component which justifies the great stress on the IOL in the pseudophakic models.

4.1. Post-surgery

4.1.1 Influence of Gravity

As can be seen in the Table 4 , with the gravity force, no change in stress on the several structures nor in the resulting force on the zonules was noticeable, being noted only a slight variation in the maximum values of S11. Despite the higher stresses were located on the haptics of the IOL, the zonules were the structures whose mean value was higher in both models. After analysing the stress of the equatorial zonule of the several models, it is possible to verify the insignificant gravity influence on the pseudophakic eye model.

Table 3: Name of the models, material and positioning of the IOL, gravity and zonular weakening of the simulations of the 3D-FE intact and pseudophakic eye models.

	IOL material	Gravity	IOL positioning	Zonular weakening
1.1	-	Yes	-	No
2.1	Hydrophilic acrylic	Yes	Horizontal	No
2.2	Hydrophobic acrylic	Yes	Horizontal	No
2.3	Hard silicone	Yes	Horizontal	No
2.4	Soft silicone	Yes	Horizontal	No
2.5	Hydrophilic acrylic	No	Horizontal	No
2.9	Hydrophilic acrylic	Yes	Vertical	No
2.13	Hydrophilic acrylic	Yes	Horizontal	Yes (50%)
2.27	Hydrophilic acrylic	Yes	Horizontal	Yes (90%)

Table 4: The maximum and mean value of S11 stress in kPa in the IOL, capsular bag and zonules in the model 2.1 and 2.5.

	Variables	Maximum	Mean Value
2.1	IOL	528.40	5.26
	Capsule	163.40	98.06
	Zonules	202.60	101.27
2.5	IOL	528.30	5.26
	Capsule	163.50	98.06
	Zonules	202.60	101.27

4.1.2 Influence of IOL positioning

To study the influence of the IOL positioning in the pseudophakic eye, a comparison between the models 2.1 and 2.9 was performed. Since the structures of the lens complex are almost axisymmetric, the difference between these two models is the gravity alignment. While the first model has the IOL in an horizontal position, the second model has its IOL gravity-aligned (vertically). The Table 5 summarizes the stress values of the structures of the models mentioned previously.

Table 5: The maximum and mean value of S11 stress in kPa in the IOL, capsular bag and zonules in the model 2.1 and 2.9.

	Variables	Maximum	Mean Value
2.1	IOL	528.40	5.26
	Capsule	163.40	98.06
	Zonules	202.60	101.27
2.9	IOL	527.90	5.26
	Capsule	163.50	98.06
	Zonules	202.50	101.27

In the IOL, the values of maximum stress decreased in the model 2.9 from 528.40kPa to 527.90kPa. These values represent changes of less than 0.1%. On the contrary, the stress value on the capsular bag increased, being the change of the maximum value variation of approximately 0.06%. In the zonules, the percentage change was even lower than the one found in the IOL, less than 0.05%. Regarding the average value, the values of all the structures remained constant between the two models, 5.26kPa on the IOL, 98.06kPa on the capsule and 101.27kPa on the zonules.

To better understand the zonules behavior, there was a need to perform another outcomes analysis. The Fig.6 was added, ensuring a depiction of the stress distribution. As the stress is higher closer to the haptics, on one hand, when the IOL was in an horizontal position, the maximum stresses were located near to the interior and exterior/lateral fibers. On the other hand, when the IOL was placed vertically, the zonular stress was higher closer to the superior and inferior poles.

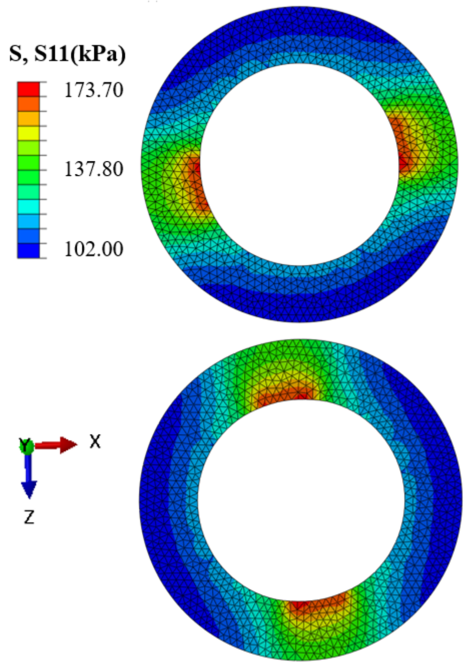

Figure 6: The S11 stress in the zonule equatorial of the models 2.1 and 2.9.

4.1.3 Influence of IOL material

Since the hydrophobic acrylic is the stiffer material, the expected outcome would be that which would support more stress in it with a consequent decrease of stress in the capsular bag. In the Table 6 is depicted the maximum and mean values of stress of the four first models drawn. These outcomes will allow us to check the validity of the first sentence.

The model 2.1, 2.2, 2.3 ans 2.4 have as IOL material: hydrophobic acrylic, hydrophilic acrylic, stiffer silicone and silicone, respectively.

The hydrophobic acrylic lens model (2.2) stands out among other pseudophakic models since, on average, the predicted stresses in this model were the highest in the IOL and zonules and the lowest in the capsule. The average value on the zonules had a percentage decrease of approximately 1.29% whereas this percentage on the IOL was of 3.48%. The average value on the capsular bag had a percentage increase of about 3.03%.

Comparing the two silicone models, both the average stress on the IOL and on the zonules were higher in the model 2.3 and the capsule has its higher average value in the model 2.4. These percentage changes were of 15.71%, 4.08% and 8.74%, respectively, which points out the increase of stress on the IOL. Since the Young's modulus of the IOL material of the model 2.3 is about 6 times higher than the one of the model 2.4, the change on the IOL stress was expected. Between the model 2.3

and 2.4, the maximum value of stress on the IOL reduced its value in approximately 68.36% as well as the maximum on the zonules, whose value was reduced by a percentage of 22.13%. The maximum value on the capsular bag had a reduction of 4.49% which is negligible when compared with the previous percentages.

Looking to the four models, the maximum stress on the zonules was almost the same. On the contrary, with the decrease of the Young's modulus of the IOL material, both the maximum and the mean value of S11 on these fibers were reduced. Considering the capsular bag stresses, as the IOL stiffness declined, the mean value of stress on the capsule was increased. And, in contrast, the maximum stresses on the IOL decreased their values.

Table 6: The maximum and mean value of S11 stress in kPa in the IOL, capsular bag and zonules in the model 2.2, 2.1, 2.3 and 2.4.

	Variables	Maximum	Mean Value
2.2	IOL	683.60	5.45
	Capsular bag	171.40	95.18
	Zonules	222.00	102.6
2.1	IOL	528.40	5.26
	Capsular bag	163.40	98.06
	Zonules	202.60	101.27
2.3	IOL	338.50	5.03
	Capsular bag	178.30	103.12
	Zonules	169.90	99.00
2.4	IOL	107.10	4.24
	Capsular bag	170.30	112.13
	Zonules	132.30	94.96

4.1.4 Influence of Zonular Weakening

In this subsection it is intended to understand the influence of the zonular weakening on the eye after cataract surgery. The model 2.1 corresponds to the pseudophakic eye model without zonular weakening whereas the model 2.13 and 2.27 have the influence of zonular weakening, being their zonular thickness reduction of 50% and 90%, respectively. The Table 7 summarizes the stress S11 of the different structures of the three models.

As can be observed from Table 7, with the increase of zonular weakening, there was an increase on the zonular stress. In contrast, with the reduction of zonular thickness, the stresses on the capsular bag and on the IOL was decreased. In both the capsule and the IOL, the percentage decrease of stress is approximately 86% whereas the average value on the zonules in the model 2.27 was about 48.03% higher than in the model 2.1. Since the model 2.27 has zonules 90% thinner than the ones of the model 2.1, the outcomes obtained were expected.

Table 7: The maximum and mean value of S11 stress in kPa in the IOL, capsular bag and zonules in the model 2.1, 2.13 and 2.27

	Variables	Maximum	Mean Value
2.1	IOL	528.40	5.26
	Capsule	163.4	98.06
	Zonules	202.60	101.27
2.13	IOL	296.60	3.02
	Capsular bag	97.84	58.71
	Zonules	199.90	121.75
2.27	IOL	68.29	0.73
	Capsule	32.35	14.00
	Zonules	229.40	149.91

With the aim of studying the stress evolution of the different parts of the zonules it was selected nodes of a vertical and an horizontal lines which are represented in the Fig. 7. Their curves are depicted in the Fig.8.

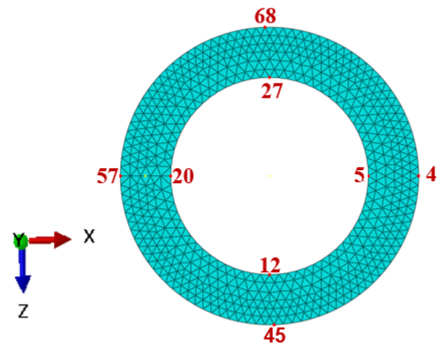

Figure 7: The nodes selected to study the S11 in the zonule equatorial of the pseudophakic eye model.

All the curves had an approximately linear growth and the overlapping of the opposite nodes stresses confirms the symmetry of the model. The slope of the curves are variable, being the line of the nodes 12, 27 and 45, 68 steeper than the others. Between the model 2.1 and 2.27, the horizontal nodes had an increase between each other of about 30 and 36%. On the other hand, the percentage increase between the model 2.1 and the model 2.27 of each vertical node is about 80% in the nodes closer to the capsule (nodes 27 and 12) and approximately 70% in the furthest nodes (nodes 68 and 45). Between the superior and inferior nodes there is no significant percentage change, less than 1%.

Although the stress values on the fibers close to the haptics, the interior and exterior zonules, are higher, with the zonular weakening, the stresses on the superior and inferior fibers increase faster than the predicted values of the interior and exterior zonules.

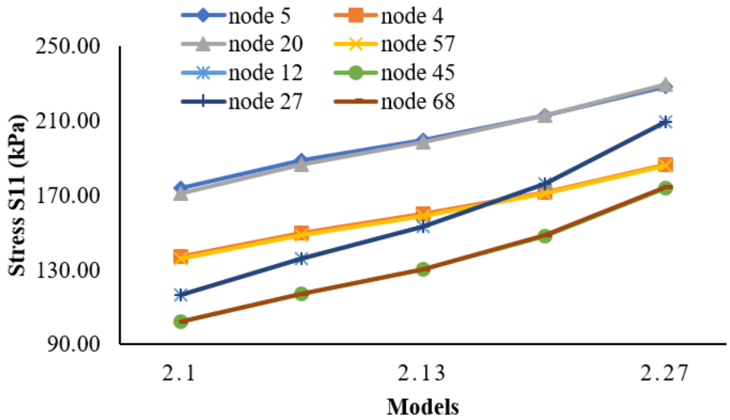

Figure 8: The S11 stress in kPa in the zonule equatorial of the models 2.1, 2.13 and 2.27

5. Discussion and conclusions

First of all, it is important to mention that the idealized FE models are the only in literature which allow to simulate the zonular behavior so realistically. The modelling under cataract surgery contributed to study the influence of some relevant factors which may be predictors of the late in-the-bag IOL dislocation. The conditions reproduced have never been considered in the available literature and they represent a great complement to the existent literature.

In the present work a 3D FE model of the human crystalline lens was develop to help building a pseudophakic eye model. The main goal with the last model was to investigate the possible biomechanical causes of the zonular weakening. Being the structures under study and since their rupture is the main precursor of the late in-the-bag IOL dislocation, the zonules are defined with a non-linear and non-isotropic behavior.

The first step was to establish a suitable geometric model. Since some experimental *in vivo* tests only describe in detail the curvature of the lens, it was necessary to select data from another experimental measurements to know the parameters of the nucleus or of the capsule and zonules. Moreover, it should be noted that some of these experiments were made using slit-lamp microscopy which may include errors by refraction. For this inherent difficulties, it was therefore adopted a idealized geometry of the lens and capsule, with a perfect ellipsoid shape for the crystalline lens. The capsule is defined with constant thickness assuming the minimal influence of this membrane on lens deformation. The cortex, the nucleus and the capsule of the model are assumed to be isotropic and linearly elastic due mainly to the lack of mechanical properties data. In this context, the great innovation was the hyperelastic anisotropic material which defines the zonular fibers. Despite the same shell geometry, the progress made allows defining the fibers properties of the zonules with no change of the adjacent matrix properties. Since there is few data with *in vivo* experimental, the majority of the information was found in *in silico* studies.

Regarding the outcomes, the gravity load do not appear to play a significant role on zonular stresses, even with weakened fibers. It can be justified by the high values of stress of the zonules in the pseudophakic eye model. Geometry simplifications, namely the perfect circle which defines the lens and capsule in their coronal section, can justify the no conclusion about what is the best IOL positioning. Only a more complete study of the composition of zonules and their geometry could help to draw more conclusions about this. The model with the less stiff IOL material is recommended to avoid this complication since its outcomes are the closer to the ones found in the intact eye model. All the simulations with pseudoexfoliative zonules have higher values of stress on the zonules so, there is evidence that the zonular weakening may lead to the failure of the zonules and consequently, to the late in-the-bag IOL dislocation. However, further work is needed to confirm this. The rupture of the zonules can not be simulate since there is no data in literature about the tensile strength on the zonules.

Lastly, even though simplifications were made both in the properties of the materials and in the geometry of the lens, the methodology used in current 3D model of the human lens is intended to be reasonable. The present project is the first 3D approach of the problem, and thus, can be used as a starting point to advance studies about the subject, until reaching the ideal characteristics of an eye after cataract surgery in order to avoid late complications. Of critical importance is the need for new measurements of the lens geometry and mechanical properties of the lens in an intact eye as well as in a pseudophakic eye.

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