COMPUTER SIMULATIONS OF REFRACTIVE SURGERY AND ACCOMMODATION MECHANISMS

FRANCOIS JOUVE, PHD
Ecole Polytechnique
Centre de Mathématiques Appliquées
91128 Palaiseau, France

AND

KHALIL HANNA, MD
Hôtel Dieu Hospital
Service d'ophtamologie
1 pl. du Parvis de Notre Dame
75004 Paris, France

1. Introduction

Numerical simulation have been widely used for decades in the engineering field, showing its ability to build virtual models allowing infinite variations around an initial guess for very low cost. In biomechanics, the powerful techniques of numerical analysis have only seldom been applied to medicine problems, providing really helpful tools for physicians and surgeons. The unfortunate scarcity of exchanges between physicians and numerical analysts may be due to mutual difficulties in understanding each-other. But once the communication has been established, the cooperation is definitely enriching for both parts.

In the late 80's, a numerical model for the eye has been built, allowing reliable simulations of various corneal refractive surgery techniques: radial keratotomy for moderate myopia, keratomeleusis for high myopia and hyperopia, arcuate incisions for astigmatism etc... A major strength of computer simulation is its ability to allow independent parameter analysis, making it easy to identify the effect of each variable on the outcome, dispensing of many laboratory experiments and sparing donor's corneas.

This 3D mechanical model use nonlinear elasticity and a special boundary condition to take into account the fact that the eye globe is filled with an incompressible body: the aqueous humor and the vitreous body. The main assumptions of this first model are presented in Section 2 of this paper. Some results on now widely used refractive surgery techniques are proposed in Section 3.

Since the presence of the crystalline lens was not necessary to compute variations of the dioptrical power of the eye, it was not included in this early model.

In Section 4, we propose a first simplified analysis of the mechanics of accommodation and some paths to new researches.

2. A mechanical model of the eye

In this section, we present the basic ideas of the mechanical model of the eye, that have been developed, in collaboration with surgeons, to help physicians predict the effects of refractive surgery.

2.1. REFRACTIVE DEFECTS

The main refractive defects (or *ametropia*) of the eye are myopia, hyperopia and astigmatism. The causes of myopia are multifactorial but amount to a discordance between the resulting refractive power of the diopters – cornea and lens – and the axial length of the eye. Astigmatism results from a lack of symmetry of the cornea around the visual axis.

The first experiments of refractive surgery date from the late XIXth century but effective surgery has only been performed since the 60's. These techniques are often criticized for the lack of comprehensive studies about the effects of surgery after short and long periods of time.

The most known technique is the *radial keratotomy*, which consists in practicing radial incisions on the cornea, preserving a unincised central zone. The intraocular pressure induces a blowing of the peripheral part of the cornea, and a flattening of the central zone, which is essential for refractive power of the eye. This central flattening leads to a reduction of the power and a correction to myopia. This operation is very effective in the correction of moderate myopia (less than 5 Diopters), and still widely practiced. However, it is about to be superseded by the direct remodelling of the cornea by excimer laser. Other techniques are now used to cure almost every refractive defects. Some of then will be briefly presented in Section 3.

2.2. MODELLING

Our mechanical model is designed to predict the respective effects of different surgical parameters, for various techniques used in practice. It must be reliable enough to allow the enhancement or the validation of future operations. An extensive description of the model can be found in [1]. Its main features are described below.

2.2.1. *Tridimensional nonlinear elasticity*
According to most biomechanical studies, the living material constitutive of the human eye, demonstrate a nonlinear behaviour under external loads barely superior than those encountered *in vivo* for a patient at rest.

Our aim being the simulation of operations or examinations, leading to much larger deformations, it is necessary to use a nonlinear model for the materials (hyperelastic laws) and the strain tensor (large displacements).

Some operations involve incisions of the cornea (keratotomy) and we also wish to be able to simulate non-axisymmetric geometries (astigmatism). For those reasons, a tridimensional model has been preferred to a shell model or to a 2D axisymmetric model. The curved shape of the eye, and the necessity to capture very small changes in geometry (for example to compute accurately radii of curvature), led us to choose high order finite elements (Q2 - 27 nodes hexahedrons) rather than a classical piecewise linear discretization.

2.2.2. *Boundary conditions*
The ocular globe is filled with the *aqueous humor* and the *vitreous*. It becomes essential to take it into account if one wants to simulate external loads inducing external pressure on the eye: for example during *tonometry*, which measures the intraocular pressure for the detection of glaucoma. Incompressibility characterizes the action of the aqueous humor and the vitreous: a new boundary problem is stated, with a constraint on the internal volume of the structure. A simulation consists then in three successive steps:

- The initial intraocular pressure of the patient is assumed to be known.
- The shape of the eye at rest under the action of intraocular pressure and other external forces (muscles...) is computed, as well as the initial internal volume.
- To simulate an operation, the internal volume is maintained to the value computed at the previous step and the new intraocular pressure becomes an additional unknown of the problem.

An existence result for the minimization problem of hyperelasticity, with a constraint on the internal volume, has been obtained following the ideas of J.Ball [8] (cf. [1]).

2.2.3. *Constitutive laws and mechanical constants*
The histologic structure of corneal stroma shows that it is constituted by randomly distributed lamelae, parallel to the mean fiber of the shell. Each

lamella is composed of a large number of collagen fibrils of uniform diameter and oriented parallel to the long axis of the lamella itself. The collagen fibrils are inter-spersed among a ground substance, and spacing of the fibrils can be considered uniform. This leads to the choice of a transversally isotropic law, with an isotropic plane perpendicular to the thickness. Such an hypothesis is confirmed by experiments. Anisotropy of the corneal material is strong: the measured Young moduli, in the direction parallel to the fibers, are about 100 times greater than Young moduli measured in the direction orthogonal to the surface.

One difficulty is then to evaluate elasticity constants for this type of constitutive law (at least 5 constants in the simplest case). Homogenization techniques enable to take into account the microscopic structure of the material, and to compute the mechanical constants that cannot be measured experimentally. Two stages of homogenization are necessary to compute the macroscopic coefficients.

- *First stage:* the lamelae are modelled as cylindrical collagen fibers included in a soft matrix. Classical homogenization is used to calculate the coefficients of the lamelae.
- *Second stage:* corneal coefficients are derived from the previous stage from explicit formulae for stratified materials.

3. Simulation of refractive surgery

In this section, we present a series of sample results, that have been obtained using this numerical model. The interested reader can find more details in [2][3][4][5][6][7].

3.1. RADIAL KERATOTOMY

The model shows its ability to isolate the effect of each of the operation parameter, independently from the others.

The radial keratotomy consists in making, with a diamond knife, 4, 6 or 8 radial incisions on the cornea. The parameters of the operation are the number of incisions and their direction, position, depth and length. An exhaustive exploration of all these parameters is clinically impossible. Their effect have been tested with the model and the results are reported in [3][5].

Figure 1 shows the cross-section of a cornea after radial keratotomy, compared to a cross-section of the initial cornea. The center flattens, reducing the refractive power. This kind of operation is used in the treatment of moderate myopia (less than 5 Diopters).

Figure 2 shows the stress distribution on a cornea after 8 incisions of radial keratotomy. Data about stress distribution could be a great help in

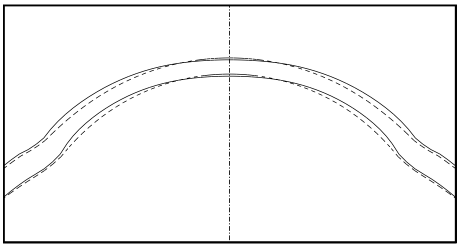

Figure 1. Cross section of the cornea after radial keratotomy (dotted line: cornea before operation)

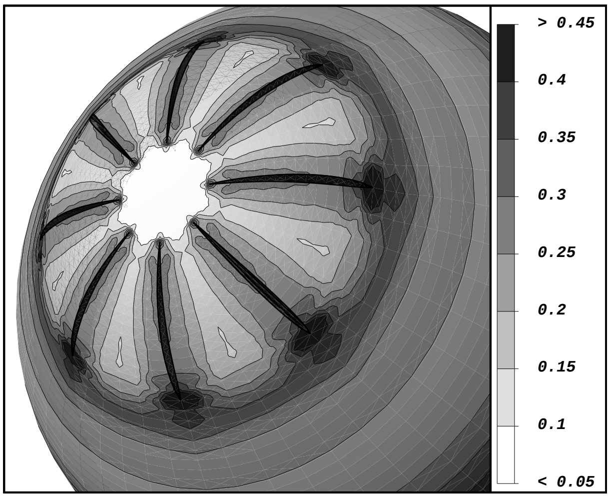

Figure 2. Contour plot of maximal stresses after radial keratotomy (8 incisions)

predicting the long time effects of surgery. Although our model is purely elastic, the cornea shows a slight viscoelastic comportment. High stresses, especially concentrated at the center of the cornea, could cause a progressive change of the effects of the surgery until complete healing.

3.2. ARCUATE KERATOTOMY FOR ASTIGMATISM

Another type of keratotomy, consists in practicing two (or more) incisions perpendicular to a meridian, in order to correct astigmatism. Along the incised meridian, under the effect of the intraocular pressure, the cornea is flattening, while it steepens along the unincised meridian. If these respective effects are carefully controlled, astigmatism is corrected, at least partially. Since it is less invasive than remodelling with excimer laser, this operation has more future than radial keratotomy.

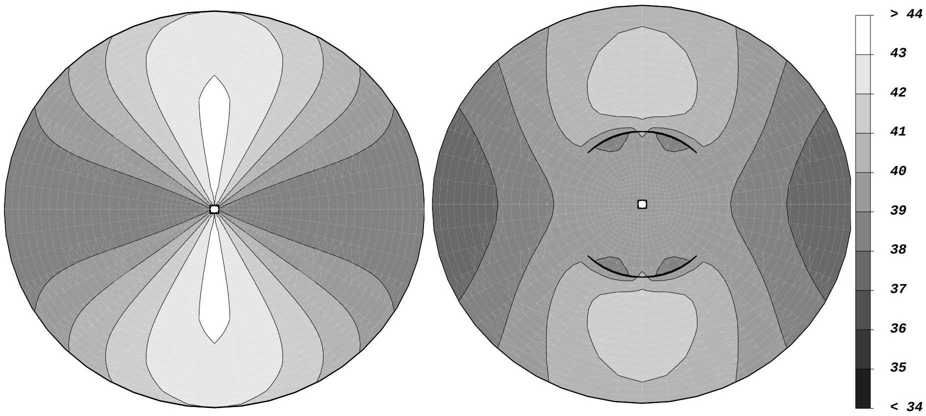

Figure 3. Map of refractive powers. *left:* before operation, the cornea shows a 5 Diopters astigmatism on axes $0x$ and $0y$. *right:* after 2 arcuate incisions perpendicular to $0y$, astigmatism is almost completely corrected (scales are expressed in Diopters).

Among the respective effects of all the incision parameters, computer simulations demonstrate the inefficiency of additional incisions: when more than two incisions are made, the resulting correction is very similar to the one obtained after when only the two incisions closest to the center are made. Like in the radial keratotomy case, all parameters have been studied independently to collect useful information for surgeons (see [2][4][6]).

Figure 3-left shows a map of refractive powers on a 5 Diopters – perfectly symmetric – astigmatic cornea. On Figure 3-right, the map, obtained after two arcuate incisions, has been plotted, showing an almost symmetric cornea in the central zone.

3.3. AN ANTERIOR CHAMBER IMPLANT

As an example of other techniques used to correct large myopia (superior to 10 Diopters), we have studied a particular shape of anterior chamber implant shown on Figure 4. An important issue of such surgery is to ensure a stable position of the implant in everyday life, for example when the patient is rubbing his eyes.

4. A preliminary model of the accommodation mechanism

Computer simulation applied to refractive surgery have proven its efficiency. We propose to use computational mechanics to simulate accommodation, and to evaluate aging changes such as: the shape of the lens, mechanical properties of the lens material, and the lens capsule. The effect of aging changes will be analysed independently, as variables to identify the produc-

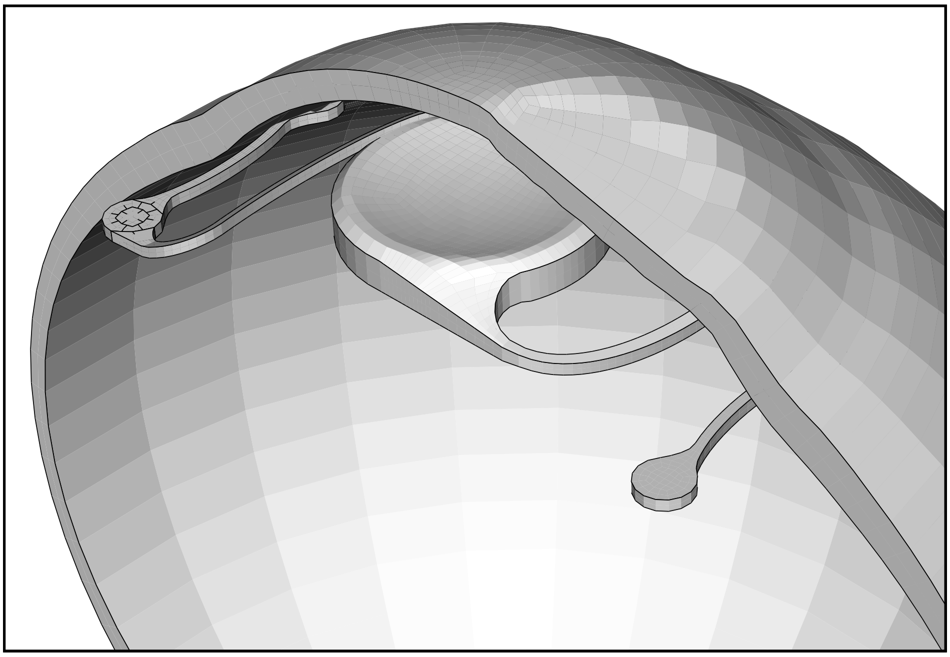

Figure 4. Anterior chamber implant in (half) a deformed eye.

tion of presbyopia. We also intend to simulate the pseudo-accommodation phenomena, that is observed after cataract surgery with Intra Ocular Lens (IOL). The results will be published in [9].

Accommodation is produced by an increase in the curvature of the lens surfaces. The accepted theory of the mechanism of accommodation is the von Helmholtz's theory: accommodation results from the contraction of the ciliary muscle, that releases the tension of the zonular fibers, and that allows the lens to assume rounder shape. As a first model, we assume that the lens is an elastic body contained in the capsular bag on which the ciliary muscles are acting. Out of its capsule, *i.e.* in an unstressed state, the lens exhibits its *unaccommodated* shape, while it lies in an *accommodated* state (close vision) when it lies in its capsular bag in the absence of other exterior forces. The first step in the modelling consists in developing a numerical method that can solve nonlinear elasticity for large displacements of an initially stressed body. Figure 5-left shows the geometry of the lens in both the accommodated and unaccommodated states. Figure 5-right shows the stress distribution in the accommodated state, which will be the initial stress distribution in the simulation of the accommodation process. Due to the symmetries of the problem, computations are performed using a 2D-axisymmetric formulation.

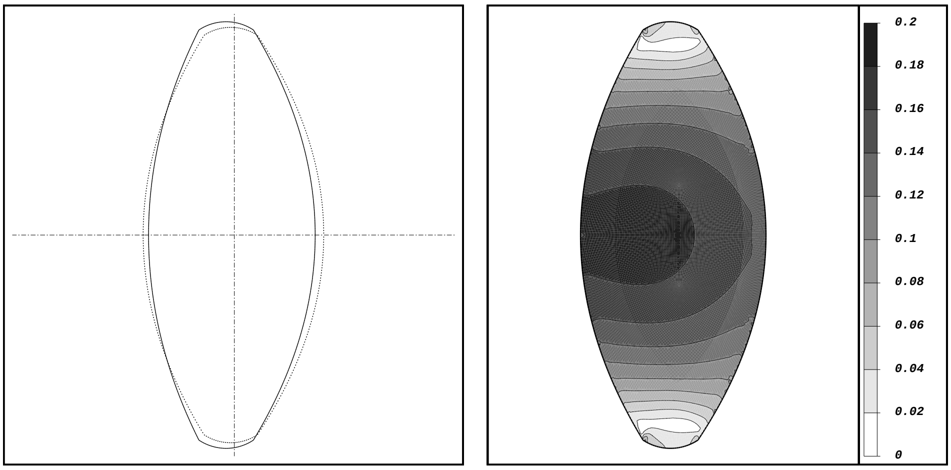

Figure 5. *Left:* cross section of a crystalline lens unaccommodated (plain line) an accommodated (dotted line). *Right:* maximal stress distribution in the lens in its capsular bag.

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