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The biomechanical modelling of the refractive surgery

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Abstract

A study reports the numerical modelling of corneal-shaped sculpting according to simulation of the refractive surgery to verify biomechanical as well as geometrical parameters of the eye and to obtain the expected changes in the refractive power of the eyeball model.

The finite-element method (FEM) was used to simulate an effect of refractive surgery. The corneal ablation and deformation for myopia correction were modelled.

The refractive correction has an insignificant sensitivity on the assumed eccentricity of the corneal anterior profile across the range $e = 0$–0.5. The expected correction occurs for corneal Young's modulus $E_C \geqslant 2$ MPa. The including elasticity of the Descemet membrane $E_D = 2E_C$ or $5E_C$ has an insignificant influence on the refraction correction of the cornea with $E_C > 2$ MPa, and has a greater influence for $E_C < 1$ MPa.

The understanding of the relationship between geometry, material properties and intraocular pressure (IOP) applied on the human eye has an importance for results of the refractive surgery. Numerical calculations showed that modelled dynamics of the eye is important for obtaining quantitative information about the biomechanical parameters of the biological eye tissues and permits its modelling before refractive surgery.

Keywords: Refractive surgery; Eye model; Corneal topography; Biomechanics; Finite-element method

1. Introduction

The method of refractive surgery is a procedure to correct ametropia by ablating the central area of the human cornea. This plays a principal role in the refractive behaviour of the eye. In recent years, many studies have demonstrated the efficacy, safety, complication and risk factors of refractive surgery [1–9]. The aim of refractive surgery is to manipulate the curvature of the anterior cornea to produce better quality of vision. The history of refractive surgery procedures dates back to the 1980s. Since this period, methods of refractive surgery have developed and improved with time, yet we cannot forget that they are invasive procedures and complications may occur. Most common cases are dry eyes, over/under correction, visual acuity fluctuation, halo/starbursts around light sources, light sensitivity, ghosts/double vision, wrinkles in flap, decentred ablation, debris/growth under flap, thin/ buttonhole flap, induced astigmatism, epithelium

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erosion. These complications are important from a biological as well as an optical point of view. The over and under correction occurs as an error of the optical system. This is caused by changes in the corneal geometry. The modelling of the corneal shape during refractive surgery exerts influence on its mechanical parameters, specific for each case. Nevertheless, the elastic parameters of the tissues of the eye are not taken into account. It could be one of the reasons for which the over or under correction occurs after refractive surgery. Usually a slight overcorrection (a slight level of hyperopic) is applied to calculate parameters for corneal ablation. This is applied because the cornea after surgery has a trend to change the curvature with relation to the calculated curvature. Probably this is caused by the change of corneal mechanical parameters and corneal elastic response during and after refractive surgery [10]. The interesting point for these presumptions is the report [11] that describes the experiment *in vitro* of ablation at a depth of 50, 100 and 150 μm on the human eyes. The authors reported that they obtained a significant flattening of the corneal curvature for the ablation of 50 and 100 μm, but with the ablation at a depth of 150 μm and the same intraocular pressure (IOP) level, this caused an opposite effect. This latter depth resulted in bulging of the cornea; this resulted in the increase of the curvature, prior to surgery. The authors suggested that for some depth of the ablation, probably between 100 and 150 μm, and for an IOP level of 20 mmHg, the fibres of the corneal stroma are weak enough to induce the central corneal to bulge. These results confirm presumptions that further investigation into the knowledge about mechanical parameters of the tissues of the eye is necessary to permit correction as well as to secure proper working functions of the eye's optical system.

It is considered that the corneal stroma is responsible for mechanical stabilization of the cornea [12]. However, Hjortdal and Ehlers [13] conclude from the *in vitro* exams that apart from the stroma the Bowman's membrane is also of great importance. During refractive surgeries like LASIK (laser *in situ* keratomileusis), Bowman's membrane is cut to create a flap of the cornea. In the photorefractive keratotomy surgery, the membrane undergoes ablation. In both cases of the refractive surgery this weakens the Bowman's membrane. Concerning the stroma, it is thinner after ablation and more susceptible to the changes of the IOP. The literature [13–35] and the results based on the biomechanical model of the eyeball, previously published by us [36], clearly show that elastic parameters of the tissues of the eye have significant influence on the quality of imaging. Thus, the knowledge of the corneal structure and the mechanical parameters has fundamental meaning for refractive surgery. In order to obtain the optimal effect of correction, it is necessary to establish the biomechanical parameters of the eyeball for each patient. It is still questionable whether successful surgery can be accomplished from the present knowledge.

2. Method

The computerised three-dimensional model was constructed in the Cosmos system (Cosmos, Structural Research & Analysis Corporation). Cosmos is the standard and commercial software used in this field of research; the construction problem is solved by the finite-element method (FEM). The eyeball was modelled using the 20-node, SOLID-type elements, with a constant pressure (so, after deformation the structure keeps its axial symmetry). Details of the biomechanical model of the eyeball were described in our previous paper [36].

In the model, we assumed that the materials imitating the eye tissue are physically linear. The model consists of the following four material fields: cornea (stroma), Descemet's membrane, sclera and "pupil" – the limbus ring [36]. The limbus ring (located on the boundary between the two mentioned areas) is a passive component replacing the stiffness of the tissues placed around the crystalline lens, which has been recognized as an innovation in the modelling of the eyeball. The limbus ring is necessary to ensure that the optical system of this model has the ability of the self-adjusting effect prior to refractive surgery. It means that a sharp image is maintained on the retina, independent of the eyeball expansion [36,37]. It is expected that the model will lose the possibility of self-adjustment after the ablation procedure.

We investigated the influence of the elastic and geometrical parameters of the model as well as the changes of the IOP of the refractive power of the eye system. The physical linear material has a constant elasticity of elongation modulus, independent of loading. The placement of the linear and isotropic material is possible within a limited scope of the IOP pressure variation (which is about one-quarter of the nominal pressure – as current results show) when no high-stress gradients and finite deformations are present. The optical system used for this model was similar to the Gullstrand-La Grand optical system [38], but we applied different values for the radius of the anterior corneal surface $R = 7.86\,\text{mm}$. Pressure IOP was reduced to a dimensionless factor p being the multiplier of the nominal pressure, and hence $p = 1$ denotes pressure $2135\,\text{Pa} = 16\,\text{mmHg}$.

Ablation modelling consisted of the modification of the corneal anterior profile (Fig. 1). For this approach the number and arrangement of the finite elements in the construction of the cornea are the same and the only