ABSTRACT

Concerning surgical and therapy planning for interventions at human eyes, especially at cornea and lens, computer based simulations are needed to predict the postoperative behaviour of the eye (vision) before surgical acts at the patients. In the Institute of computer science in the Research Center Karlsruhe a simulation system is developed for the refractive surgery methods. Biomechanical simulations are performed with the commercial tool ANSYS, where morphometric and material data of the human eye are very important. The deformation of the cornea after interventions is the input for further optical simulations to give answer concerning the quality of vision.

KEY WORDS

Biomedical behaviour, biological tissue deformation, corneal biomechanics, surgical planning, FEM simulation, lens system, human eye components.

1. INTRODUCTION

The human eye is an ensemble of complex biological components, where the final aim of a good vision is given by an optimal co-operation of the special eye components. The biomechanical system of the human eye consists of the cornea at the front, the anterior chamber, a lens system, the vitreous and the retina with „fovea centralis” before signal processing in the brain [1]. The cornea is the most responsible part for the refractive behaviour with about 43 dpt [2]. For the fine tuning of refractive behaviour, the lens system including the accommodation mechanism is responsible. Furthermore the shape of bulb influences the imaging process of the external patterns onto the retina (bulb to long, to short).

In the situation today (see fig. 2), a lot of ametropia diseases can be detected in different ways. For myopia and hyperopia, the shape of bulb in combination with corneal surface shape is responsible, but corrections with the aim of better refractive behaviour are performed only by interventions at cornea and lens. Astigmatism is based on non spherical shape of cornea in combination with special lens shape, so, the refractive behaviour has to be corrected by local interventions at cornea. Presbyopia is a special effect of aging process an is based on diseases in the lens system that means lens and its surroundings (ciliary tissue, zonula fibres).

In all these diseases there exist principally 2 possibilities for correction. The first one is given by glasses without operational acts and the other is done by surgical interventions. So it is very important, to regard the whole anterior eye section with cornea and lens as a base of operational acts. The “virtual eye” is a coupled system of biomechanical and optical simulations to predict the vision quality based on biological tissue deformation at the eye components. The simulations with parameter variations give information concerning needed surgical parameters and are important for surgical planning. Also the simulated results in comparison with real patient data can be stored for reference of subsequent diseases.
ametropia (60% of the population)
myopia hyperopia astigmatism presbyopia

glasses ← corrections → refractive surgery

cornea ← interventions → lens

"Virtual Eye": biomechanical and optical modelling and simulation

surgical planning database for surgical interventions

Fig. 2: Different types of ametropia and corrections

2. MODELLING OF CORNEAL TISSUE

The most important intention by surgical interventions in the cornea is to manipulate the curvature of the anterior cornea by structural mechanical acts. The structural mechanical behaviour depends on biological tissue in a very closed manner.

The basic model (Gullstrand) of a spherical shape of cornea was extended to hyperbolic shape with n layers. Fig. 3 shows a hyperbolic n-layered geometry solid before surgical acts. Fig. 4 shows the corresponded cornea with a structured mesh after a surgical intervention (hyperopia correction).

Radial symmetric intraocular pressure (IOP) as surface load on the inner endothelium area of the cornea leads to a deformation of the inner layer nodes. By node connecting with other of the next layer and the specific layer dependent material properties the node stress strain is continued at the next layer and so on. The input of the optical simulation must be the outer deformation because of refraction indices for the different surfaces.

The real material parameters are very important for simulations of the corneal tissue [3], [4], [5]. So, a material dependent refinement of the cornea is useful and necessary. From biological point of view, there are different biological layers with different geometrical thickness parameters. Furthermore each layer consists of different material behaviour like Young’s modulus, Poisson ratio and so on. The consequence is a consideration of these layer related geometrical and material parameters. For FEM-modelling, the net topology must guarantee a continuous transition in stress/strain parameters at the common nodes at material interface. In a first step, we use isotropic elastic material in each layer for simulation.

Additional to the one layer model, consisting of a unique material solid, a parameterised model of layer related composition is performed [5,6]. For the given geometrical and material parameters, the number n of layers is specified. So, the different biological tissue composites can be regarded in a very fine manner (epithelium, Bowman lamella, stroma, Descement membrane and endothelium). But also within the stroma the keratocyte densities can be regarded as material with own characteristics.

Fig. 3: Hyperbolic shape of n-layered cornea

Fig. 4: FE-mesh for hyperopia correction by laser

Although the morphometric data of the patient cornea may be performed by geometrical measurements, the material behaviour of the patient specific tissue is the big unknown. To get information about the influence and the importance of the different (numerical unknown) material parameters, simulations as the only methods have to be performed.

Based on different simulation methods, the tissue behaviour and especially for the eye tissue the vision can be analysed and evaluated before surgical acts at real patients.

In the past time, for simulations of the corneal behaviour mostly homogeneous material and/or tissue with constant thickness were used [6]. But because of the complex interaction of the fibrils within the different layers also in one layer no homogeneity can be expected. Additionally, there must be distinguished between areas near the centre (optical axis) and near the limbus. There is different mechanics of the biological fibrils. Also the stress near limbus is direction dependent that means, we expect radial stresses in other amount like border parallel stresses orthogonal to the former [7].

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A problem will be to cut corneal tissue in different parallel layers for experimental measurements.

Fig. 5a: Separation of pig cornea from pig bulb
Fig. 5b: Separation of layers from the cornea

The employment of human corneae for experimental research is very critical and difficult [8]. To minimise the experiments at human tissue, first experimental series at pig corneae were performed. It’s easier from the ethic point of view, to cut porcine corneae and to measure stress strain parameters for material destination. Probably basic results concerning layer dependent steadiness and structural behaviour may be transposed to human corneal tissue, although numerical values have to be destined in special human corneal experiments. Fig. 6 shows the experimental results of measured E-modulus from strained pig corneal layers. There were separated outer and inner layers with different thickness. The destined material parameters like E-modulus are important inputs for the FE models to simulate deformations of tissue based on intra ocular pressure (IOP).

3. MODELLING OF LENS SYSTEM

Similar to the cornea modelling, the lens itself is modelled as a n-layered solid with spherical areas, based on different radii at the anterior part and the backward part. A smaller difference between the radii is given by different layers.

Fig. 7a shows a section through the lens, consisting the kernel and furthermore two layers for simulating age process. The symmetry of the solid is given by the optical axis.

Fig. 7b shows the structured mesh of the lens solid, where each layer has its own mesh, but at material interface there are common nodes for continuous deformation functions. As well the solid can be parameterised by the different radii (at front, backwards, layer dependant), also the mesh can be parameterised including refinement. The mesh nodes near the limb are connection nodes for later muscle attachment. This will be important for understanding accommodation process to correct presbyopia diseases.

Fig. 7a: Solid of n-layered lens
Fig. 7b: Mapped mesh for the n-layered lens

4. MODELLING OF MUSCLE AT LIMBE

The third modelling part of the anterior eye section component is the muscle tissue. In this approach, it doesn’t mean exactly the shape of ciliary tissue or the zonula fibres, but serves as solid interface between the bulbe (sclera), limbe, cornea and lens system, to formulate boundary conditions at cornea and to generate forces at the lens border. The muscle model is a very important modelling aspect concerning consistent mesh transitions in the different eye components. So the cornea is modelled for exaple by 3 biological layers, the lens is based on kernel plus 2 layers and the bulbe (sclera) is given by 2 layers. The consistent transition between these different material solids is modelled by a virtual muscle. Fig. 8 shows the tissue interface in 2-D intersection, the fig. 9 shows the 3-D model by rotation of the area around the optical axis. This is possible because of symmetrical conditions like in reality.
Dependent on the patient specific intraocular pressure (IOP), the pressure is modelled as surface load at the inner cornea surface and generates deformations at the attached nodes throughout the layers to the outer surface (see fig. 12). The deformation depends also on the surgical acts and the so induced thickness loss of the corneal tissue. For adjusting the geometry solids to the patient specific morphometry, patient related data are fitted to the mathematical parameters of the solid model. For surgical interventions at cornea, the sclera nodes are fixed as boundary conditions. The sclera model has a big influence to the global shape of the bulb and is responsible for myopia and hyperopia effects.

5. COMPOSITION OF COMPONENTS

The refractive behaviour of the human eye is basically destined by the bulb shape, the cornea and the lens. So, each surgical intervention disturbs the global refractive behaviour. On the other side, the global behaviour can be influenced by special shape correction at cornea and lens. Fig. 10 shows the solid model with a parameterised cornea n-layered shape, a parameterised hyperbolic sclera (bulb) and a parameterised n layered spherical lens including a virtual shape consistent muscle. Fig. 11 shows the mapped mesh of this solid.

6. CONCLUSION

The relationship between geometry, material and loaded human cornea data is important for the FEM simulations of the 3-D corneal tissue behaviour. Basic results concern the qualitative behaviour of corneal tissue regarding different constraints. For elastic material properties any deformation simulations for different surgical types (PRK, LASIK) could be performed. The FEM simulations refer to a parameterised solid and net model and regard also an n layered biological tissue. The advantage of
simulation and modelling the surgical acts are the possibility of reiteration, the parameterisation and the prediction without training at real patients. In combination with optical simulations postoperative results concerning visus are expected. The deformations based on biomedical tissue behaviour and the surgical acts (output of biomechanical simulations by the commercial tool ANSYS) are the input for the optical simulations performed by the commercial tool SOLSTIS. The rays, coming from object patterns outside the human eye, are simulated to generate images at the retina.

REFERENCES


