Effects of intraocular pressure and aspheric transition zone ablation profile on corneal biomechanics after conventional refractive surgery

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Abstract. Our Purpose is to study the effects of intraocular pressure (IOP) and aspheric transition zone (ATZ) on corneal biomechanics after pure hyperopia correction by using the finite element analysis (FEA). The values of IOP were changed, and 1-5# aspheric transition zones were designed in 1-5D hyperopia correction model. Simulate and calculate the wavefront aberration, stress and vertex displacement of cornea. The results show that with the increase of IOP and diopter, defocus increases positively and sphere increases negatively. Diopter and IOP have slight influence on coma. At 22mmHg, the maximum value of defocus was 1.367mm at 5D-1#, and the maximum value of sphere was -0.32mm at 5D-5#. IOP and diopter have great influence on the stress in the marginal region of the anterior corneal surface, and 1D-1 # has the maximum value at 22mmHg. With the increase of IOP and diopter, the vertex displacement of posterior corneal surface increased. The ATZ ablation profile has little effects on the wavefront aberration and displacement. We can draw a conclusion that refractive surgery destroys the physiological structure of cornea and has a great influence on the biomechanical properties of cornea. IOP plays an important role in maintaining the physiological structure of cornea.

1 Introduction

The cornea was cut in the process of laser in situ keratomileusis (LASIK) refractive surgery. During LASIK refractive surgery, the corneal flap seriously affects the corneal morphology, and the changes of corneal biomechanics will lead to various visual problems after operation. Finite element analysis is a common method to study the biomechanical properties of human eyes, which can solve many problems that can not be completed in vivo experiments, and the results can also provide a strong theoretical basis for clinical ophthalmology.

Intraocular pressure plays an important role in maintaining the stability of corneal biological structure, IOP has individual difference. The influence of IOP on corneal refractive surgery should not be ignored, Elena Lanchares et al [1] have suggested that IOP should be considered in the determination of the depth of ablation. Fang Lihua et al[2] have shown that intraocular pressure can deform the cornea and affect postoperative aberrations. Chen Kaijian et al[3] indicated that high IOP can lead to curvature of the corneal anterior surface, aberrations and refractive changes, and lead to a decline in visual quality. Therefore, IOP is an important factor for postoperative visual quality after refractive surgery.

With the clinical application of corneal refractive surgery, the surgical project is constantly improved. Q-value guided LASIK is one of the methods. The aspheric transition zone realizes the smooth connection between the optical zone and the non ablation zone. Xin Baoli et al[4-6] said aspheric ablation guided excimer laser corneal refractive surgery improve the vision acuity by decreasing the postoperation wavefront aberration. Lai Xiaohua et al[7] have said that aspheric ablation can improve visual function which make the patient more satisfied, because it maintain the corneal's surface.

Many scholars use the method of finite element simulation to achieve the work that can not be completed in vivo experiment, especially in the field of human eye tissue biomechanics. Ibrahim Seven et al[8] simulated case-specific treatment settings by created the patient-specific finite element models. R Aldhafeeri[9] constructed the axisymmetric and three-dimensional finite element models of the eye and buckles to calculate eye deformation. Abhijit Sinha Roy et al[10] constructed a finite element whole-eye model of a human eye investigate the impact of corneal elasticity on corneal shape changes before and after simulated LASIK.

2 Methods and materials

2.1. Simulation of LASIK refractive surgery

Based on the FEA, the LASIK laser refractive surgery was simulated. Firstly, a 3D solid model was built in the 3D modeling software NX, then the material model of

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human eye tissue was added in the finite element analysis software ANSYS to obtain the finite element model of human eye. then mesh divide, boundary conditions and intraocular pressure were set. In this study, IOP was set to 10, 15 and 22 mmHg, respectively. The mesh divide of cornea was more detailed than that of sclera, because our research focuses on cornea.

We constructed 1-5D pure hyperopia correction model of human eyes, D is diopter. The thickness of corneal flap was 100um, the diameter of corneal flap surface was 8mm, the diameter of optical zone was 6mm, and the width of transition zone was 1.05mm. According to the nonlinear material properties of cornea and sclera, we use the hyperelastic material model based on Ogden function. The strain energy function can be expressed as:

$$Q = \sum_{k=1}^{N} \frac{1}{d_k}(J-1)^{2k} + \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}(\bar{\rho_1}^{\alpha_i} + \bar{\rho_2}^{\alpha_i} + \bar{\rho_3}^{\alpha_i} - 3) \quad (1)$$

N, μ_i, α_i, and d_k were the material constants. In the process of material fitting, we choose $N = 2$ and $N = 1$ as the fitting order of cornea and sclera.

Table 1. The corneal and scleral fitting parameters

	cornea	sclera	
α_1	103.51	α_1	182.73
α_2	103.61		
μ_1	0.003535 MPa	μ_1	0.030224 MPa
μ_2	0.003535 MPa		

2.2 Aspheric transition zone ablation profiles

In this study, 1-5# aspheric transition zone ablation profiles were designed in the 1-5D hyperopia model. The ablation profile of the aspheric transition zone was defined as:

$$d(x,y) = f_b(x,y).d_e(x,y) \quad (2)$$

And,

$$d_e(x,y) = f\left(\frac{O_z x}{2\sqrt{x^2+y^2}}, \frac{O_z y}{2\sqrt{x^2+y^2}}\right) \quad (3)$$

It defines the extended ablation depth of the transition zone and O_z is the diameter of the optical zone.

In addition, $f_b(x,y)$ is the mixed function of aspheric transition region algorithm. Before realizing the mixing function, the following aspheric ablation functions must be created:

$$f_b'(x,y) = h - \frac{(x^2+y^2)}{R+[R^2-(x^2+y^2)(Q+1)]^{1/2}} \quad (4)$$

Here, h is the non-zero value of the ablation depth at the edge of the optical zone, Q describe the asphericity. R is the radius of curvature of the ablation profile.

$$R = \frac{(x_0)^2 + h^2(1+Q)}{2h} \quad (5)$$

Then, the aspheric mixing equation can be obtained by normalization method:

$$f_b(x,y) = f_b'(x,y)/h \quad (6)$$

Five ablation profiles designed by changing Q value were shown in Figure 1.

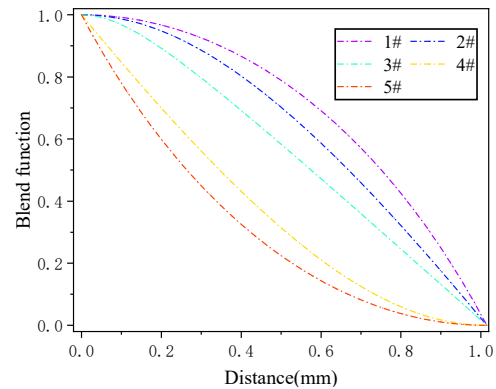

Fig. 1. 1-5# Ablation profile of aspheric transition zone.

3 Results

3.1 Corneal anterior surface aberrations after hyperopia correction

In the finite element analysis software, different IOP was set for calculation. Design algorithm based on optical path difference, the wavefront aberrations can be calculated from the x-, y- and z-displacements of the anterior corneal surface. Since the wavefront aberrations of the corneal posterior surface is small, it will not be discussed here. Wavefront aberrations were calculated by the difference between postoperative aberrations and preoperative (0D) aberrations. So, we can analyze the optical aberrations caused by biomechanical changes after conventional LASIK refractive surgery.
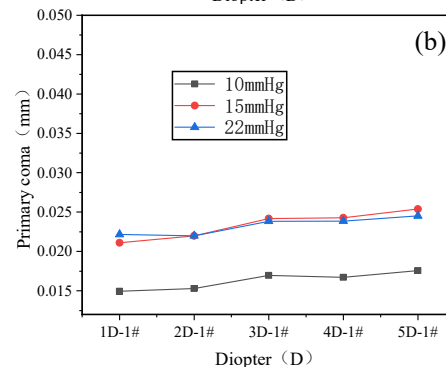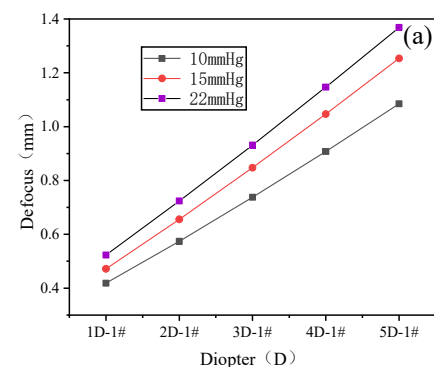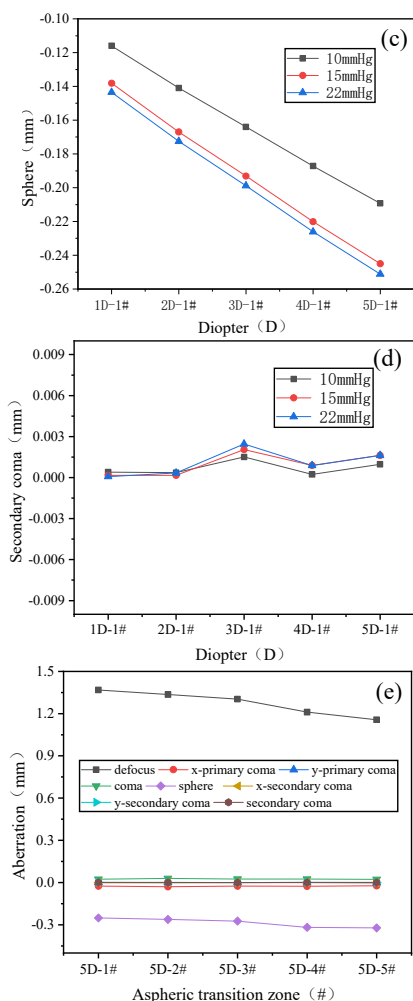
Fig. 2. (a), (b), (c) and (d) represent defocus, primary coma, sphere and secondary coma, respectively. (e) was the aberration induced by different aspheric transition zones under 22 mmHg intraocular pressure.

It can be seen from (a) that IOP and diopter have obvious effects on defocus. Under the same intraocular pressure, the defocus value increased with the increase of hyperopia diopter. At the same diopter, the higher the IOP, the greater the defocus value. At 22mmHg, 5D-1# has maximum value of 1.367mm. From (b), the intraocular pressure has no significant effect on the primary coma, and the value of primary coma at high IOP (22mmHg) and normal IOP (15mmHg) have no significant difference. With the increase of corrected diopter, the primary coma has no change, and the value was small as a whole. From (c) we can know that with the increase of intraocular pressure, the sphere increases negatively, but the effect is not obvious. However, under the same intraocular pressure, with the increase of hyperopia diopter, sphere increased rapidly to negative direction. The maximum value was - 0.32mm at 5D-5#, which can be seen in figure (e). It can be seen from (d) that intraocular pressure and diopter have little effect on the secondary-coma, and the values were small and almost all were 0 mm. From (e), when the intraocular pressure was constant, when the aspheric transition zone changed, defocus and sphere all changed, defocus decreased with the increase of aspheric transition zone ablation profile, but sphere increased in a negative

direction. The coma and the secondary coma have no obvious change, and the values of them were almost 0. In 1-4D hyperopia correction, the effects of different aspheric transition zones on aberration were similar, the figures were not shown here. In addition, the trend at 15mmHg and 10mmHg was consistent with that at 22mmHg. On the whole, the IOP was the higher, the defocus and sphere was the greater. The value of 15 mmHg was not much higher than that of 10 mmHg, there was no significant difference. The charts of 15mmHg and 10mmHg were not listed here.

3.2 Stress of corneal anterior surface after hyperopia refractive surgery

Refractive surgery destroys the integrity of the cornea and the biomechanical properties of cornea were affected. Different cutting depth will produce different value of stress. Here we show the changes of corneal anterior surface stress when the hyperopia correction diopter is 3D.
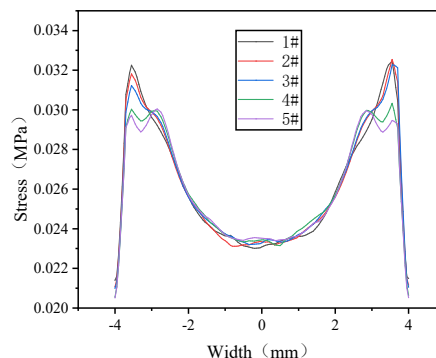

Fig. 3. The corneal anterior surface stress at 22mmHg

It can be seen that 1-5 # different aspheric transition zones have the same trend with different IOP. The stress value in the central zone is small, the stress value in the edge area is larger, and it is greatly affected by the 1-5 # aspheric transition zones. This is because that, cutting position in edge area, 1# aspheric transition zone has the largest cutting amount in the edge region, it also has the greatest influence on the biological structure of cornea. At abscissa 3 and - 3, the attachment produces the maximum value, which is caused by the corneal flap incision. The trend of IOP at 10 and 15 mmHg was the same as that at 22 mmHg, but the larger the IOP, the greater the stress. The change of 1D-5D is similar, and the images were not be shown here.

3.3 The vertex displacement of the posterior corneal surface

Under the action of intraocular pressure, the anterior and posterior surface of cornea will deform. According to the calculation, the vertex displacement of posterior corneal surface was much larger than that of anterior corneal surface, we will focus on the displacements of the posterior corneal surface. The vertex displacement was calculated by the difference between the maximum value of the anterior and posterior corneal postoperative and preoperative. It can be seen from the calculation that the

greater the intraocular pressure, the greater the deformation of the anterior and posterior corneal surface.
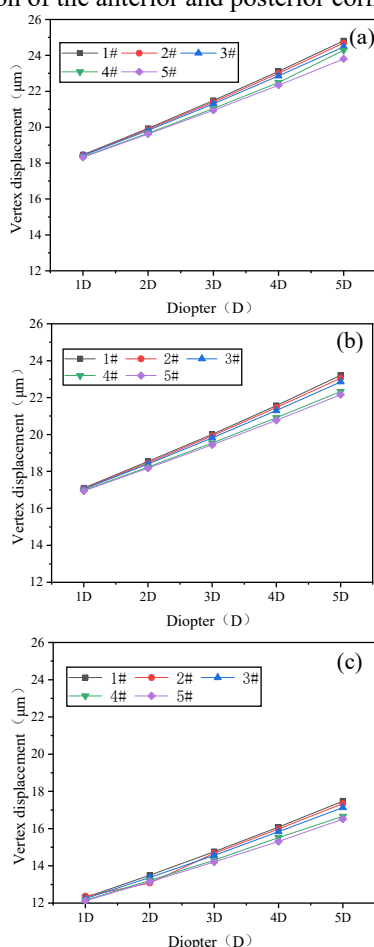

Fig. 4. (a), (b) and (c) showed the displacement of posterior corneal surface when IOP was 22, 15 and 10 mmHg .

From Figure 4, the vertex displacement was different when the IOP changed. Altogether, the higher the IOP, the greater the deformation of the posterior corneal surface. When the diopter was same, there was no significant difference in corneal deformation under the same IOP, and the deformation of 1#-5# has a slow decreasing trend. When the aspheric transition zone and IOP were same, with the increase of diopter, the deformation was greater. When the IOP was 22mmHg, 5D-1# has the maximum value, and it was 24.81μm.

4 Conclusions

Diopter and IOP have significant influence on defocus and spheren, but have slight influence on coma. With the increase of IOP and diopter, defocus increases positively and sphere increases negatively. IOP and diopter have great influence on the stress in the marginal region of the anterior corneal surface. Due to the cutting amount of the 1# aspheric transition zone ablation profile, the stress in the 1# ablation profile was the most concentrated. With the increase of IOP and diopter, the vertex displacement increased. But the aspheric transition zone ablation profile has no obvious effects on the corneal aberration and displacement. IOP[11], diopter and value of Q[12] will affect the postoperative visual quality. To

achieve the best postoperative effect, it is necessary to damage the corneal biomechanical properties as little as possible.

Acknowledgment

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