Correlation of corneal behavior under the action of orthokeratological contact lenses with tension states in thin curved plates

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Abstract. *Contact lenses are currently a practical and efficient solution for the correction of refractive errors but also for the application of ortho-keratology procedures in cases of keratoconus pathologies or high myopia. The component of the cornea is represented by a stratified cell structure determining its central dimension (on the optical axis) of the order of 0.5 mm and the marginal one of approximately 0.7-1.0 mm. The radii of curvature of the cornea are different in the two main meridians (vertical and horizontal) causing the radii of curvature of the concave surface of the contact lens to be made accordingly. Because in ortho-keratology the contact lenses used are rigid and are made so as to have effects of deformation of the corneal surface, in the latter are induced a series of residual and inertial stress states through which changes in refractive power are obtained. In this paper are presented some aspects related to the correlation and assimilation of corneal behavior, under the action of ortho-keratology contact lenses, with the states of tension developed in thin curved plates. The first part of the paper analyzes the structures of the cornea in terms of the properties of the component materials (anisotropic elastic structure) and then identifies the geometric dimensions that can be used in modeling stress states. In the second part of the paper are proposed the simplifying hypotheses of working with thin isotropic curved surfaces and with spherical or toric radii of curvature, which are the basis for writing the equations for determining stress states. In the final part of the paper are presented the observations and conclusions of the use of these fundamental principles of construction of procedures for modeling the behavior of the cornea under the action of ortho-keratological contact lenses.*

Keywords: contact lens, stress, curved thin plate.

Introduction

Clinical determinations on the biomechanical properties of the vivo structures of the eyeball are currently one of the most important fields of research in ophthalmology / optometry with immediate applications on the study and recovery of various ocular dysfunctions. As a number of specialized studies (Spoerl, E., 2015) show, the

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biomechanical properties of the corneal structure can define a tissue's responses to the internal or external action of a force or pressure. The corneal structure is considered to have visco-elastic properties, also different dimensions in section and an anisometropic structure which implies an approach to biomechanical behavioral analyzes both in terms of elastic component and viscosity component manifested in thin curved layers. Certain dysfunctions of the corneal structure, such as keratoconus, can thus be identified and studied because the change in biomechanical behavior, so the characteristics of elasticity and viscosity or even geometric dimensions are directly related to the level of corneal dysfunctions.

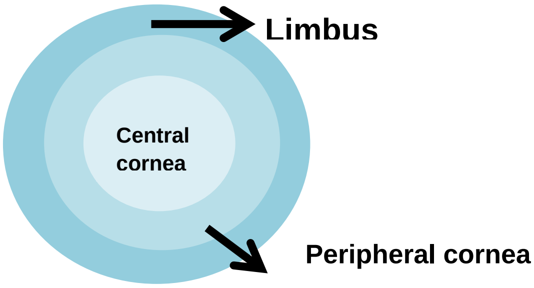

Figure no. 1. The main areas of the cornea representation (central, peripheral and limbus)

The cornea next to the sclera is the outer shell of the eyeball with the main purpose of protecting the structures inside it. The cornea is an avascularized, transparent tissue, having the same structure as the sclera, connected to it in the limbus area. The shape of the cornea, in the horizontal axis is oval and measures 11-12 mm in the horizontal direction and 9-11 mm in the vertical direction. The horizontal corneal diameter measured in clinical practice with the ORBSCAN II system revealed (Sridhar, M., 2018) the mean corneal diameter of 11.71 ± 0.42 mm. The mean corneal diameter was 11.77 ± 0.37 in males, compared with 11.64 ± 0.47 in females. The diameter of the cornea varied between 11.04-12.50 mm in men and 10.7-12.58 mm in women (Rüfer F., 2005). The limbus is the widest area in the upper and lower cornea. The cornea has a convex and aspherical mirror shape, with an anterior curvature of 7.8 mm and a posterior curvature of approximately 6.5 mm.
From a dimensional point of view, there is a gradual increase in thickness, starting from the central cornea to the periphery.

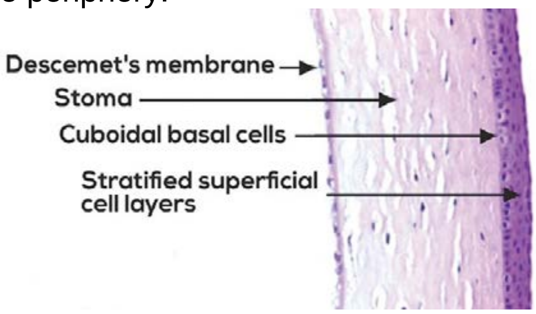

Figure no. 2. Histopathology of cornea showing corneal epithelium, stroma, and Descemet's membrane

Source: [https://www.ijo.in/viewimage.asp?img=IndianJOphthalmol_2018_66_2_190_224089_f2.jpg]

This change in tissue thickness is due to an increase in the amount of collagen in the peripheral stroma. In basic and experimental research on the dimensional variations of the cornea and using different evaluation methods, the thickness of the central cornea in normal eyes was determined as having values between 0.551 mm and 0.565 mm, and for peripheral cornea thickness between 0.612 mm and 0.640 mm. It has also been observed that the thickness of the cornea decreases with age. The corneal layers include, from the outside to the inside, the epithelium, the Bowman's membrane, the stroma, the Descemet's membrane and the endothelium, respectively. In experimental studies conducted in the recent period (Dua HS, 2013) were found several aspects related to the existence of a cell layer of cornea, which is well defined, which is called the pre-Descemet layer and which receives increased attention with development of lamellar surgeries based on laser radiation.

From the point of view of mechanical properties, the rigidity of the central section structure of the anterior cornea (stroma) seems to be particularly important in maintaining corneal curvature.

Optically, the cornea contributes about 40-44 DS of refractive power and represents about 70% of the total refraction of the entire eyeball (60 DS), and the refractive index of the cornea is 1.376.

Theoretical substantiation of the biomechanical model of cornea

As shown by specialists (Whitford, C., 2018), the topography of the cornea is determined by the balanced state between internal and external forces acting on it and its mechanical rigidity, which is in turn defined by the geometry of the cornea, thickness and biomaterial rigidity.

From a theoretical and experimental point of view, the contribution of corneal geometry and thickness to the general mechanical rigidity is determined quite simply, but the rigidity of the material is much more difficult to quantify, because it is dependent on the microstructure of the stroma. Basically, the stroma consists of about 200 lamellae, each of which in turn consists of a matrix rich in proteoglycols and containing collagen fibers arranged neatly, in two directions. The density and orientation of the collagen fibrils in the stroma are the primary factors that affect the rigidity of the material and therefore the general mechanical rigidity of the cornea. From a fundamental point of view, some research (Whitford, C., 2018) has established that the behavior of a nonlinear, anisotropic material such as the corneal stroma can be analyzed using the Helmholtz function which takes into account, in turn, the deformation tensor Cauchy-Green. This deformation tensor contains a series of parameters that describe the volumetric compressibility, the expansion coefficients and the gradients that associate the deformation with the distortion, respectively.

However, in order to determine the induction of tension in the cornea by means of orthokeratological lenses, a simplifying hypothesis is required by which the structure of the cornea is assimilated with an isotropic and hyperelastic material. A characteristic of the hyperelastic material, as approached by the cornea as a material in experimental research (Peng S., et al., 2015) is that there is a function (W) of stored potential energy. For most hyperelastic materials, this energy is synthetically defined as $W = W(C) = W(I_1, I_2, I_3)$, what is the potential energy of the second Piola-Kirchhoff stress tensor described as S from the following equation:

$$S = \frac{\partial W}{\partial E} = 2\frac{\partial W(I_1 + I_2 + I_3)}{\partial C} \qquad (1)$$

where E = is a component of the Green - Lagrange strain tensor, and C = is the normal Cauchy – Green strain tensor, I_1, I_2, I_3 = there are three basic invariants of the tensor C.

Assuming that λ_i $(i = 1, 2, 3)$ represents the main extension ratio, the main stress ε_i can be obtained from the relationship $\varepsilon_i = \lambda_i - 1$. Relationships between the basic invariants of the tensor C and the main extension ratio λ_i, according to the equations developed by (Ogden R.W., 1997), can be expressed by the relation (2):

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$
$$I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2 \quad (2)$$
$$I_3 = \lambda_1^2\lambda_2^2\lambda_3^2$$

Finally, the energy function of the material is determined from:

$$S = 2\left(\frac{\partial W}{\partial I_1}\frac{\partial I_1}{\partial C} + \frac{\partial W}{\partial I_2}\frac{\partial I_2}{\partial C} + \frac{\partial W}{\partial I_3}\frac{\partial I_3}{\partial C}\right) \quad (3)$$

and for the hyper-elastic material, according to (Doghri I., 2000), the stored energy *W* can be decomposed in the isochoric part $\overline{W}$ and the hydrostatic part W_h in the following form:

$$W = \overline{W} + W_h = f(\overline{I_1} - 3, \overline{I_2} - 3) + p(J - 1) \quad (4)$$

where $\overline{I_1} = J^{-\frac{2}{3}}I_1$ and $\overline{I_2} = J^{-\frac{4}{3}}I_2$ represents the first and second invariant of the isochoric tensor $\bar{C}$, and in the above expressions $J = I^{\frac{1}{2}}$ is the ratio of the deformation volume.

Tension states developed in thin curved plates assimilated with the shape of the cornea

According to those presented in the literature, the cornea can be assimilated with a thin curved, anisotropic and hyper-elastic plate structure. It is charged on an annular area at the level of the limbus with forces and deformation stresses that act as a result of the application of the OrthoK contact lens used in the ortho-keratology procedure.

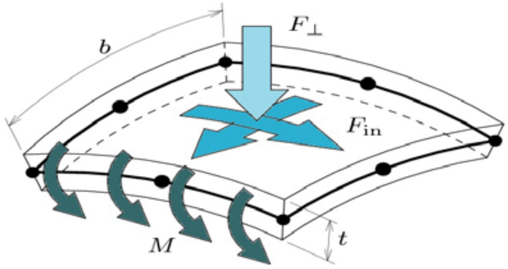

Figure no. 3. Curved thin plate element assimilated as the shape of the cornea
Source: [https://dianafea.com/manuals/d101/Theory/node42.html]

The orthokeratology procedure (OrthoK), as mentioned in a series of fundamental and experimental research (Carracedo G., 2019) has now become an effective method of correcting refractive errors from a clinical point of view.

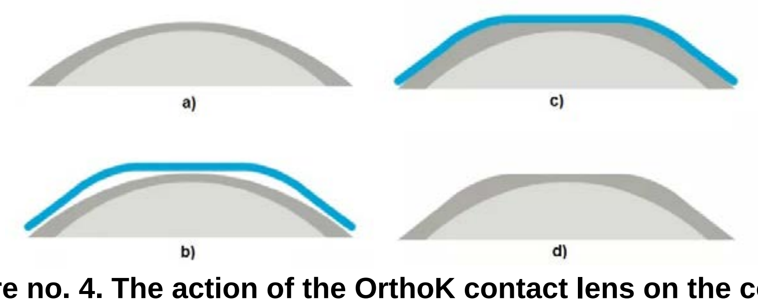

Figure no. 4. The action of the OrthoK contact lens on the cornea
Source: [https://visionspace.com.my/orthokeratology/]

OrthoK contact lenses are worn overnight by subjects with high myopia and then removed in the morning on waking. The specific advantage of ortho-keratology contact lenses - OrthoK is due to the fact that their use by this procedure is a reversible method, so that when the contact lenses are removed from the corneal surface, the latter returns to its initial physiological state through an inertial process. At this point, the ortho-keratological lens-cornea assembly is subjected to the action of internal and external pressures that are equalized by thermodynamic balancing mechanisms and by the tear fluid that adheres to both the cornea and the contact lens. The fact that the OrthoK contact lens (fig.4.b) acts on the surface of the cornea, both in the central area and in its peripheral area (fig.4.c), an important aspect, but still too little studied, is analysis of the quality of vision and total refraction during wearing and after removal of the OrthoK contact lens (fig.4., d). In the case of the OrthoK contact lens, this being a hard lens (Costan V.V., 2020), induces a tension that changes the shape of the cornea. The change in shape is the response to the deformation action applied by the contact lens (fig.4.d). This stress / tension relationship in the cornea is represented by a linear variation up to a physiological limit.

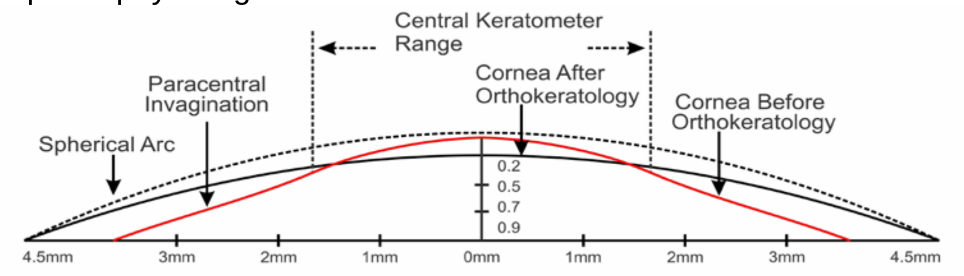

Figure no. 5. Corneal curvature modification under the action of the OrthoK contact lens

Source: [http://visionmagazineonline.co.za/2019/03/15/7405/]

Usually, the back optical radius zone (BOZR) induces a change of approx. 0.75DS thus reducing the myopia-type refractive error that can be improved by this procedure. The relief curve of the contact lens is adjacent to the BOZR template and provides space for the central cornea to change to adjust the length of the corneal arch to the shape of the concave diopter of the contact lens (fig.5). The curve in the central area is used for placement and centering, and the shape of the peripheral curve serves to transfer tear fluid (Gradinaru I., 2020), this design improving the centering and stability of the OrthoK contact lens on the cornea. (Ramkissoon P., 2019)

Results and discussions

Thus, for the study of corneal deformation under the influence of OrthoK contact lens, this paper proposes an approach to the corneal surface as an isoparametric element, with a minimum of 8 nodes in which there are three degrees of freedom of translation and three degrees of rotation around the axes of the element. select. The determination of these degrees of freedom is based on the definition of translation and rotation polynomials $u_i(\xi,\eta)$ and $\phi_i(\xi,\eta)$which produce the strain and stress distribution for each area element in the stratified structure of the cornea. Therefore, under the initial simplifying conditions, the effects of the compression exerted by the shape and dimensions of the OrthoK contact lens on the corneal surface can be determined and also the duration of action can be estimated in different specific cases

Conclusion

Therefore, the analysis models of the effect of the OrthoK contact lens on the corneal structure allow to obtain answers related to the problems of shape and size, duration and frequency of use in improving the myopia refractive error, It can therefore be concluded that in to determine the best contact lens shape for ortho-keratology and how to charge with tensions and pressures at the corneal level, the efficiency of the process of reducing the refractive error increases, offering the patient comfort and quality of vision.

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References

Spoerl E., (2015) "Stress-strain measurements by strip extensiometry", Department of Ophthalmology, Univ. Hospital Carl Gustav Carus, TU Dresden, Germany.

Sridhar M., (2018), "Anatomy of cornea and ocular surface", Indian J Ophthalmol. 2018 Feb; 66(2): 190–194. doi: 10.4103/ijo.IJO_646_17.

Rüfer F, Schröder A, Erb C. (2005) "White-to-white corneal diameter: Normal values in healthy humans obtained with the orbscan II topography system", *Cornea*; 24:259–61.

Dua HS, Faraj LA, Said DG, Gray T, Lowe J. (2013), "Human corneal anatomy redefined: A novel pre-descemet's layer (Dua's layer)" *Ophthalmology*;120:1778–85.

Whitford C., Movchan N.V., Studer H.*et al.* (2018), "A viscoelastic anisotropic hyperelastic constitutive model of the human cornea",*Biomech Model Mechanobiol* 17, 19–29.

Peng S., Yang Y., Jingjing X., Yanming S., (2015), "Corneal hyper-viscoelastic model: derivations, experiments, and simulations", *Acta of Bioengineering and Biomechanics* Vol. 17, No. 2, 2015.

Ogden R.W., (1997), "*Non-linear elastic deformations"*, Courier Dover Publications.

Doghri I., (2000), "*Nonlinear continuum mechanics"*, Springer, Berlin–Heidelberg.

Carracedo G., Espinosa-Vidal T.M., Martínez-Alberquilla I., Batres L., (2019), "The Topographical Effect of Optical Zone Diameter in Orthokeratology Contact Lenses in High Myopes", *Journal of Ophthalmology*, vol. 2019.

Gradinaru I., et al.,(2020), "Study on the surface condition of composite biomaterials related to saliva pH", *Materiale plastice,* vol.57, issue 3, pag.174-179.

Costan V.V., et al., (2020), "Improvements to biomaterials structure used in acrylic prostheses", *Materiale plastice,* vol.57, issue 3, pag.271-278.

Ramkissoon P., (2019), "The use of Reverse Geometry Lenses in Modern Contact Lenses", *VISIONonline Magazine,* March 15, 2019.