Journal of the Mechanical Behavior of Biomedical Materials 85 (2018) 102–108

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Tensile biomechanical properties and constitutive parameters of human corneal stroma extracted by SMILE procedure

Yaoqi Xiang[a], Min Shen[a,*], Chao Xue[b], Di Wu[b], Yan Wang[b]

[a] Department of Mechanics, School of Mechanical Engineering, Tianjin University, Tianjin 300350 China
[b] Clinical College of Ophthalmology, Tianjin Medical University, Tianjin Eye Hospital, Tianjin Key Laboratory of Ophthalmology and Visual Science, Tianjin Eye Institute, Tianjin 300022, China

ARTICLE INFO

Keywords:
Stress-strain curve
Constitutive model
Uniaxial tension
Anisotropic
Human corneal stroma
Hyperelastic

ABSTRACT

The biomechanical behavior of human corneal stroma under uniaxial tension was investigated by the experimental analysis of cornea stromal lenticules taken out by corneal refractive surgery. Uniaxial tests were conducted to determine their stress-strain relationship and tensile strength. The Gasser-Ogden-Holzapfel (GOH) model was used to describe biomechanical behavior of the corneal stroma. The theoretical stress-strain relationship of the GOH model in the uniaxial tensile test was deduced. The corneal specimens were collected from ten patients (4 male and 6 female), aged from 17 to 36. The differences between corneal stress-strain relationship in the horizontal and vertical direction were compared. The constitutive parameters C_{10}, k_1 and k_2 were evaluated through least squares curve-fitting of experimental data.

1. Introduction

Refractive error has become one of the most common diseases in the Department of Ophthalmology. In recent years, with the rapid development of modern corneal refractive surgery, a large number of laser treatment techniques for myopia have emerged. Small incision lenticule extraction (SMILE) corneal refractive surgery, as a new surgical method, has become the focus of attention in recent years. Detailed surgical procedure was described in previous researches (Bryant and McDonnell, 1996; Wang et al., 2017; Wu et al., 2014). Although this new technique has provided satisfactory early refractive outcomes, predictability, and stability in most published reports (Sekundo et al., 2011; Shah et al., 2011), the complications after surgery still have not been solved. Keratoectasia, as one of the most unfavorable complications after refractive surgery (Tomita et al., 2010), is a pathology that induces differences in biomechanical properties of the cornea, such as elasticity and rigidity. Because of these changes, surgery outcome becomes unpredictable and may be disastrous for the patient (Brawer and Pirovino, 2009). To predict the deformation and internal force of cornea after the SMILE corneal refractive surgery, one of the important research topics of corneal biomechanics is the determination of constitutive parameters.

Cornea is a transparent tissue that covers the front surface of eyeball and provides most of the optical power for the eye. The cornea is composed of five different layers. From the external to internal those layers are: epithelium, bowman's membrane, stroma, descemet's membrane and endothelium. The stroma is the major part of the mechanical and optical properties of the cornea. Most of the collagen fibers in the cornea are found in the stroma (Meek and Boote, 2009) which is formed by different orthogonally crossed lamellae and makes up about 90% of the corneal thickness. The collagen fibers are organized in two preferential directions: (1) Nasal-Temporal direction(horizontal), and (2) Superior-Inferior direction (vertical) (Meek and Newton, 1999). On the contrary, the corneal limbus collagen fibers are arranged in the circumference direction. These characteristics provide the cornea with a highly anisotropic behavior in addition to a nearly incompressible response (Bryant and Mcdonnell, 1996).

At present, tensile test is the most common method of measuring biomechanical properties of corneas (Elsheikh and Alhasso, 2009; Hoeltzel et al., 1992; Zeng et al., 2001). The tensile test is a conventional method for testing material properties, which can reflect the stress-strain relationship and tensile strength of the material. Nevertheless, there are still some problems, which lead to obvious differences in different studies. First, it is difficult to obtain the intact human cornea. Second, the cornea is soft tissue with compact size, and it is difficult to cut the cornea into a standard strip in the experiment. Finally, individual differences in material properties of the cornea vary significantly. Fortunately, with the clinical application of SMILE, cornea stromal lenticules may become a more suitable alternative subject for experimental research. The SMILE corneal refractive surgery

* Corresponding author.
E-mail address: minshen@tju.edu.cn (M. Shen).

https://doi.org/10.1016/j.jmbbm.2018.05.042
Received 19 March 2018; Received in revised form 7 May 2018; Accepted 29 May 2018
Available online 30 May 2018

doesn't change the microstructure of the lenticule, so we expect that the SMILE corneal refractive surgery has little effect on the mechanical properties of the lenticule. In this paper, we took the cornea stromal lenticules which removed from small incision lenticule extraction corneal refractive surgery as the research object. In order to reduce the impact of individual differences, we chose ten patients (4 male and 6 female) with diopters from − 2 D to − 6 D and aged from 17 to 36 years old.

We measure the stress-strain relationship and tensile strength of the stromal lenticule through the uniaxial tensile test and reveal the corneal stroma biomechanical properties. The main advantage of this paper is that we deduce the theoretical stress-strain relationship of the GOH model in the uniaxial tensile test and use the MATLAB fitting experimental data to evaluate the constitutive parameters of the material. And it could be easily modified to describe any tissues or objects within other soft tissues.

2. Method

2.1. Specimen preparation

It is difficult to obtain the intact human corneas. The specimens used in this experiment were the lenticules left over from the SMILE at Tianjin Eye Hospital, Tianjin Medical University. All surgeries were performed by the same experienced surgeon who used the VisuMax femtosecond laser system (Carl Zeiss Meditec AG, Jena, Germany) to correct the preoperative refractive error. We recorded the number of refractive surgeries which were performed by the same doctor in one month. The mean and SD age of the patients was about 22 ± 5 years (see Fig. 1).

The study was approved by the Ethics Committee of Tianjin Eye Hospital, Tianjin Medical University and adhered to the tenets of the Declaration of Helsinki. Informed consent was obtained from each patient to use any clinical data for analysis and publication.

After the creation of the refractive lenticule and the small incision, the surgeon dissected the lenticule from the surrounding tissue and extracted it through small incision. Then the lenticules were marked with gentian violet in the 12 o′clock direction (see Fig. 2). Next, the lenticules were preserved in medium Eusol-C (Alchimia, Padova, Italy) (Kanavi et al., 2014) below 4 °C in refrigerator for no more than 24 h. During this period, they were taken out to prepare for testing one by one.

The average diameter of the lenticule was about 6.0 mm, and the central thickness of the lenticule was given by SMILE surgery data. In order to determine stromal anisotropy, pairs of lenticules were extracted from two eyes of the same human and used to produce specimens in different anatomical directions as a group of experiments. The roughly circular corneal lenticules were marked as the hour hand on the face of the clock (Jayasuriya et al., 2003). The left lenticules were labeled by appointing 9–3 o′clock sections as horizontal and the right lenticules were labeled by appointing 12–6 o′clock sections as vertical. A strip specimen with 1.20 mm width was obtained from the central region of each lenticule using a double-blade tool (see Fig. 2).

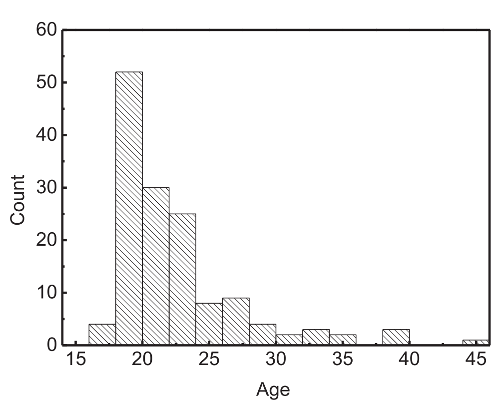

Fig. 1. Histogram of patients' age distribution.

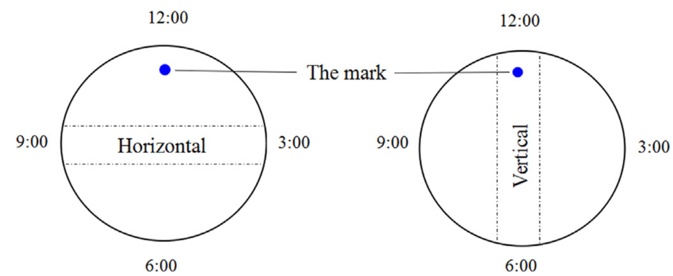

Fig. 2. Horizontal and vertical strips of the stromal lenticule.

2.2. Uniaxial tensile testing

The tests were performed with an in-situ micro tension cyclic testing system (IBTC-50, Care Measurement & Control Co., Ltd., Tianjin, China) in water bath apparatus filled with normal saline (see Fig. 3). The room temperature was 25 ℃.

The specimens were connected to mechanical clamps with rough surfaces to prevent slippage. With a specimen length of 6.0 mm, the distance between the clamps was 1.5 mm. The sample needed to be preconditioned to obtain a stable load-elongation relationship. Specimens were subjected to uniaxial tension starting with three times displacement cycles between 0 and 0.50 mm to condition the specimens, followed by loading to failure. The elongation rate was 0.6 mm/min. The three times cyclic load-elongation curves were shown in Fig. 4. It can be seen that the second load-elongation curve was close to the third load-elongation curve. After the third cycle, the specimen can be regarded as preconditioned. The output comprised the axial tension load in Newtons and the specimen elongation in mm.

The typical complete curve of the tensile failure experiment was shown in Fig. 5. The initial low-stiffness toe region was followed by a region of higher stiffness. The curve approximately consisted of four sections. At the OA segment of the curve, load changed slowly and the elongation rose rapidly. At the AB segment of the curve, a nonlinear relationship with the load-elongation increased exponentially. At the third section, BC segment of the curve approximated to a straight line. At the final section, CD segment of the curve reflected a nonlinear relationship between load and elongation. At the point D, the specimen was broken.

The tests produced results in the form of axial load P and elongation δ, we had:

$$\sigma = \frac{P}{A} \tag{1}$$

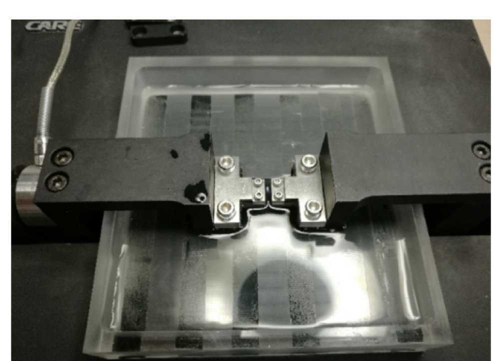

Fig. 3. Photograph of in-situ micro tension cyclic testing system.