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Dynamic material properties of the human sclera

Jill A. Bisplinghoff[a,*,1], Craig McNally[b], Sarah J. Manoogian[b], Stefan M. Duma[b]

[a] Virginia Tech–Wake Forest University, Center for Injury Biomechanics, 100F Randolph Hall, MC 0238, Blacksburg 24061, VA
[b] Virginia Tech, Blacksburg, VA

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ABSTRACT

As a result of trauma, approximately 30,000 people become blind in one eye every year in the United States. A common injury prediction tool is computational modeling, which requires accurate material properties to produce reliable results. Therefore, the purpose of this study was to determine the dynamic material properties of the human sclera. A high-rate pressurization system was used to create dynamic pressure to the point of rupture in 12 human eyes. Measurements were obtained for the internal pressure, the diameter of the globe, the thickness of the sclera, and the changing coordinates of the optical markers using high-rate video. A relationship between true stress and true strain was determined for the sclera tissue in two directions. It was found that the average maximum true stress was 13.89 ± 4.81 MPa for both the equatorial and meridional directions, the average maximum true strain along the equator was 0.041 ± 0.014, and the average maximum true strain along the meridian was 0.058 ± 0.018. Results show a significant difference in the maximum strain in the equatorial and meridional directions ($p = 0.02$). In comparing these data with previous studies, it is concluded that the human sclera is both anisotropic and viscoelastic. The dynamic material properties presented in this study can be used for advanced models of the human eye to help prevent eye injuries in the future.

1. Introduction

Over 1.9 million people suffer from eye injuries in the United States each year (Mcgwin et al., 2005). As a result of trauma, approximately 30,000 people become blind in one eye every year in the United States (Parver, 1986). In 2007, approximately 66,000 people suffered from vehicle-related eye injuries in the United States (Mcgwin et al., 2005). Of the vehicle occupants sustaining an eye injury during a crash, as many as 15–25% sustain severe eye injuries (Duma and Crandall, 2000; Duma et al., 2002) and it was shown that within these severe eye injuries as many as 45% resulted in globe rupture (Kuhn et al., 1994).

Eye injuries have been a growing area of interest, because of the increase in the frequency of these injuries in both the civilian and military sectors (Kennedy et al., 2007). In 1999, material properties for the sclera and cornea were developed using a uniaxial test setup to be incorporated in a finite element model (Uchio et al., 1999). Each globe was bisected at the equator and two strip samples of the sclera were taken from the corneoscleral limbus. Similar to a method used by Nash, Uchio measured the stress–strain relationship of the sclera by applying an axial force and measuring the change in length, cross-sectional area and load (Nash et al., 1982; Uchio et al., 1999).

As a result of the sclera and cornea uniaxial material property study, several ocular computer models were created, most of which were focused on studying the effects of corrective eye surgery (Hanna et al., 1989; Sawusch and Mcdonnell, 1992; Wray et al., 1994; Bryant and Mcdonnell, 1996). The first dynamic computer model of the eye was created by Uchio and Kisielewicz (Kisielewicz et al., 1998; Uchio et al., 1999). This model found peak rupture stress using the uniaxial static material properties to be 9.4 MPa. A more recent and accurate model was created by Stitzel et al. called the Virginia Tech Eye Model (VTEM) (Stitzel et al., 2002). The VTEM was experimentally verified and developed to use a more realistic dynamic fluid–solid interaction modeling technique to simulate eye injuries. However, all previous studies were based on quasi-static properties (Battaglioli and Kamm, 1984; Ahearne et al., 2007) and for more accurate rupture stress, dynamic material properties obtained without boundary condition limitations are more desirable. Therefore, the purpose of this study is to determine dynamic material properties for the human sclera.

2. Materials and methods

High-rate intraocular pressurization was accomplished with a hydraulic system that consisted of a drop tower that was used to pressurize the human

* Corresponding author. Tel.: +1 540 231 3414; fax: +1 540 231 2953.
E-mail address: Bisplinj@vt.edu (J.A. Bisplinghoff).

[1] Expected Master of Science May 2009, Mechanical Engineering, Virginia Tech.

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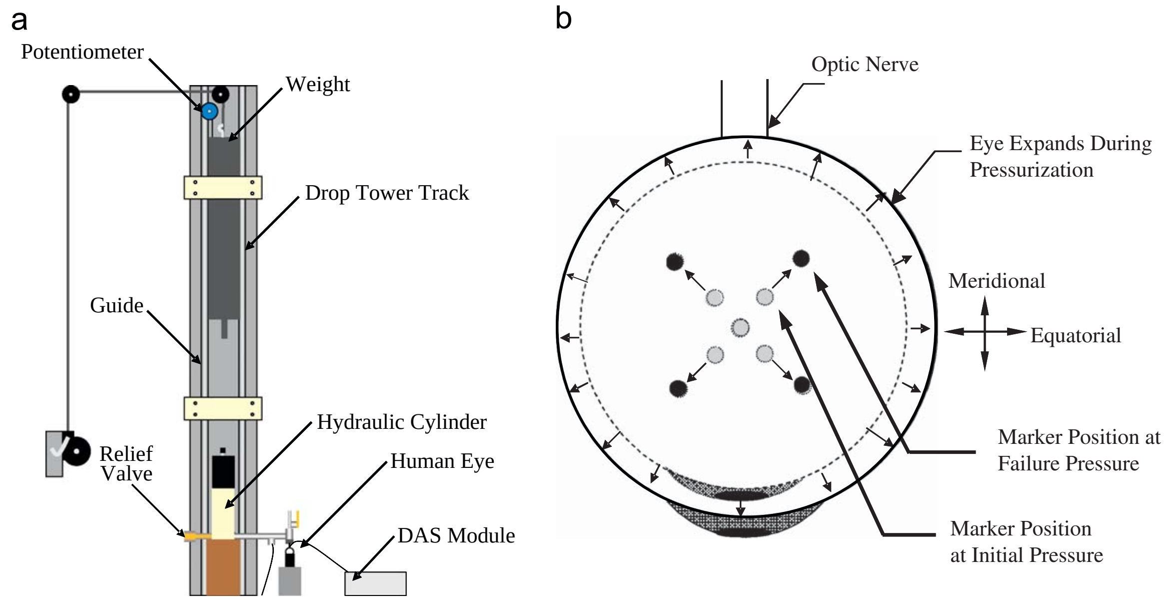

Fig. 1. Schematic representation of high-rate pressurization system (left) used to determine material properties and the expansion of a human eye shown with optical markers (right).

eye in a dynamic event (Fig. 1). To initiate the event, a weight was suspended above the piston at a desired height of 17.78 cm and then released and dropped onto the piston which was inserted into the hydraulic cylinder. The impact of the weight onto the piston caused the water to be displaced throughout the system which created a high-rate increase in intraocular pressure resulting in the rupture of the eye. This system created an average loading rate of 36.50 MPa/s. This rate was selected to match internal pressure rates observed in baseball and automobile applications (Kennedy et al., 2006).

Preparation of the system included adding water through the cylinder to act as the medium for pressurization and to produce an initial intraocular pressure of 0.001993 MPa (8 in of water). Connecting the eye to the system was a 16-gage intravenous needle inserted through the optic nerve. In order to secure the optic nerve to the needle a medical suture was used, while a cylindrical placement guide held the eye in place below the needle. To ensure that the optic nerve was sealed, it was covered with flexible coupling material and then secured with a plastic fastener.

Each human eye was stamped with five optical markers to provide a method for measuring strain (Fig. 1). In order to capture this event, high-speed video and data acquisition were used. A Photron Ultima APX-RS camera (Photron Inc., San Diego, CA) captured video at 10,000 frames per second with a resolution of 512×512, while the data acquisition system (DAS) collected data at 30,000 Hz. The internal pressure of the eye was measured from a small pressure sensor inserted into the eye through the optic nerve. This was accomplished with a pressure transducer made by Precision Measurement Company (Model 060, Ann Arbor, MI). The pressure transducer was rated for a range of 0–3.45 MPa, which was more than adequate for our expected pressure results and had a frequency response of 10 kHz.

Optical target tracking software was used to follow the movement of the diameter as well as the optical markers during the expansion of the eye (TEMA, Image Systems, Sweden). The accuracy of the tracking software was within 0.09 pixels and the video produced a pixel size at 12 pixels/mm. The internal pressure, optical marker tracking, and diameter data were correlated with respect to time.

The thickness of each specimen was examined with a high-accuracy laser to determine the thickness of the sclera after testing. The specimens were sectioned at the location of the optical markers and kept in saline solution during the test procedure. Measurements were taken with a Microtrak II high-speed laser with accuracy of 2.5 μm. This method reduced the effect of swelling that can occur with other histological processing methods.

Engineering stress (σ_E) was calculated using the internal pressure (P) with respect to time, along with the external radius (R) with respect to time (t) and the original thickness (T_1). Assuming that the eye is a spherical pressure vessel, the following equation was used to calculate the engineering stress in the eye:

$$\sigma_E = \frac{P(t)R(t)}{2T_1} \tag{1}$$

The true stress σ_T was calculated using the same spherical pressure vessel equation, but the change in thickness as the radius increased was added to the analysis (Eq. (2)). A relationship was derived to relate the radius and the thickness, where R_2 is the external radius at time t, R_1 is the external radius at $t=0$, and r_1 is the internal radius at $t=0$, which is represented by Eq. (3). Assuming that the sclera is incompressible and that there is no mass flowing into or out of the scleral shell, volume is constant throughout time. Through utilizing the equation for the volume of a shell, the thickness for each change in the radius was found (Eq. (4)) and used in Eq. (2) to find the true stress.

$$\sigma_T = \frac{P(t)R(t)}{2T(r,\ t)} \tag{2}$$

$$r_1 = R_2 - T_1 \tag{3}$$

$$T = R_2 - \sqrt[3]{R_2^3 + r_1^3 - R_1^3} \tag{4}$$

Strain of the sclera was determined from the high-speed video and the analysis software (TEMA) that was used to track the location of each of the five optical markers at each point in time. These data were then analyzed using a custom MATLAB code to calculate the true strain in both the equatorial and meridional directions. The deformation gradient tensor (F) for each group was determined by analyzing the position vectors (Eq. (5)), where x_i and y_i were the original positions of the markers and X_i and Y_i were the deformed positions of the markers. The true (logarithmic) strain tensor (E) was found using Eq. (6). A relationship between stress and strain was found for each of the twelve human eyes

$$F = \left(\begin{bmatrix} X_1 & X_2 \\ Y_1 & Y_2 \end{bmatrix}_{t=n} \right) \left(\begin{bmatrix} x_1 & x_2 \\ y_1 & y_2 \end{bmatrix}_{t=0} \right)^{-1} \tag{5}$$

$$E = \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix} = \ln \sqrt{F \cdot F^T} \tag{6}$$

A characteristic average was calculated using a custom MATLAB code to clearly represent the stress–strain data (Lessley et al., 2004). This approach has been used in previous studies and was used in the current study to better determine the average response and corridors to fit the data.

Twelve human eyes were acquired for testing, and no corneal transplantation or other operations were done to the eyes prior to procurement. The eyes were kept in a saline solution in glass jars and refrigerated for no longer than 15 days before they were tested. A previous study showed no correlation between donor age and rupture pressure, as well as, time from death and rupture pressure (Kennedy et al., 2004). A statistical analysis was performed using a matched pair student t-test to determine if a significance difference between the strain in the equatorial and meridional directions existed. All test procedures were reviewed and approved by the Virginia Tech Institutional Review Board.