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Research Paper

Time-dependent fracture toughness of cornea

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The fracture and time-dependent properties of cornea are very important for the development of corneal scaffolds and prostheses. However, there has been no systematic study of cornea fracture; time-dependent behavior of cornea has never been investigated in a fracture context. In this work, fracture toughness of cornea was characterized by trouser tear tests, and time-dependent properties of cornea were examined by stress-relaxation and uniaxial tensile tests. Control experiments were performed on a photo-elastic rubber sheet. Corneal fracture resistance was found to be strain-rate dependent, with values ranging from 3.39 ± 0.57 to 5.40 ± 0.48 kJ m^{-2} over strain rates from 3 to 300 mm min^{-1}. Results from stress-relaxation tests confirmed that cornea is a nonlinear viscoelastic material. The cornea behaved closer to a viscous fluid at small strain but became relatively more elastic at larger strain. Although cornea properties are greatly dependent on time, the stress–strain responses of cornea were found to be insensitive to the strain rate when subjected to tensile loading.

1. Introduction

Cornea is a transparent and tough tissue situated at the front of the eye. Its toughness is extremely important to protect fragile parts inside the globe, including the optical lens and retina, from catastrophic damage due to physical external force. There are many circumstances where cornea could rupture. Cornea can be cut by fast-flying sharp objects during a car accident, or easily torn by an eye-socket hit by a fast-moving squash ball (Karlson and Klein, 1986). Moreover, a progressive thinning of cornea (keratoconus), the most common corneal disorder in the US, is believed to be associated with aggressive eye rubbing, which causes mechanical fatigue damage of cornea over time. This change in corneal shape and its mechanical properties affect its optical performance, which is the cornea's ultimate function. (Gefen et al., 2009; McMonnies, 2008; Romero-Jiménez et al., 2010)

A severe shortage of donor cornea has led to attempted developments of corneal prostheses and corneal scaffolds for tissue engineering, as alternative materials to corneal transplantation (Hicks et al., 1997; Myung et al., 2008; Tonsomboon and Oyen, 2013). Understanding of fracture mechanics of cornea is therefore essential for the design of such materials. These corneal substitutes should have toughness comparable to that of cornea to withstand cyclic tensile loadings from intraocular pressure and protect the rest of the globe. However, there has been no systematic study on fracture toughness of cornea.

Fracture mechanics has been studied more thoroughly in other soft collagenous tissues, including cartilage, skin, aorta and amniotic membrane (Chin-Purcell and Lewis, 1996; Purslow, 1983a,b; Oyen et al., 2007; Oyen-Tiesma and Cook, 2001). Fracture toughness, or the ability to resist crack propagation of soft tissues can be determined by either single edge notch (Mode I), pure shear (Mode I) or trouser

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tear (Mode III) tests (Beatty et al., 2008; Comley and Fleck, 2010; Koutroupi and Barbenel, 1990). The trouser tear test is most commonly used because of the ease of sample preparation and data analysis. This method was originally developed by Rivlin and Thomas (1953) to measure the critical strain energy release rate of rubber. Purslow (1983a) subsequently demonstrated the applicability of this test to measure toughness of soft connective tissues.

The biomechanical response of cornea is predominantly governed by the stroma, which contributes about 90% of total corneal thickness. Corneal stroma consists of a hydrated matrix reinforced with highly organized collagen fibrils (Boyce et al., 2007). Similar to other soft collagenous tissues, mechanical properties of cornea are time-dependent. Stress–strain responses of cornea are nonlinear and strain-rate dependent. Creep studies on cornea showed that its behavior is nonlinear viscoelastic; cornea undergoes faster creep at greater applied stress (Boyce et al., 2007; Elsheikh et al., 2008; Yoo et al., 2011). However, the effect of strain rate on fracture toughness of cornea has not been investigated.

This work aims to examine the fracture toughness of cornea and to obtain a better understanding of the time-dependent response of cornea. Porcine cornea is selected as a model for human cornea because it has similar size, microstructure and short-term stress–strain response (Elsheikh et al., 2008). A photoelastic rubber, a linearly viscoelastic synthetic polymer with no microstructure above atomic length-scales, is used in this study to verify the methodology. This material is commonly used in biomechanical studies (Mattice et al., 2006) as it provides a good contrast to soft biological tissues with a fibrous microstructure but similar elastic modulus. Trouser tear, monotonic strain-to-failure and stress-relaxation tests were performed on cornea and the rubber sheet at various strain rates to characterize both fracture toughness and time-dependent properties of the cornea.

2. Materials and methods

2.1. *Specimen preparation*

Twenty-four pig eyes were obtained from a local abattoir (Leech & Sons, Royston, UK) and were stored at −72 °C. The eyes were thawed and equilibrated to room temperature for an hour in phosphate buffered saline (PBS). Twelve cornea specimens for monotonic strain-to-failure and stress-relaxation tests were prepared by cutting the 12 corneas into 24 rectangular strips along the superior–inferior direction with a dimension of 5 mm × 30 mm (Fig. 1(a)). The sclera (region A) was used as a gripping region to ensure that the resulting mechanical response is solely due to cornea. Therefore, each cornea specimen (region B) had a gauge dimension of 5 mm × 10 mm. The remaining 12 corneas were prepared into the geometry as shown in Fig. 1(b) for trouser tear testing. The sclera was used as the gripping region, as before. Each cornea specimen for trouser tear testing had a width of 10 mm (region B). A 4-mm sharp notch was introduced with a sharp blade prior to the test. Small pieces of sand paper were attached to region A of all specimens to assist in gripping, to prevent the slippage of specimens from the grips and to ensure that all specimens fail at the gauge section during strain-to-failure testing. Region B of all specimens was submerged in PBS for 2 h prior to testing.

As a control, all tests were also performed with a uniform PS-4 photoelastic polymer sheet (VishayMicro-Measurements, Raleigh, NC) with thickness of 0.51 mm. PS-4 rubber specimens were prepared to have similar geometry to the cornea specimens for each type of mechanical test. Six PS-4 specimens were used for each test type.

2.2. *Mechanical tests and data analysis*

All mechanical tests were performed with a universal testing machine (model 5544, Instron, Canton, MA) equipped with a 500 N load cell, and at room temperature. The specimens were gripped with custom flat, parallel stainless steel grips coated with water-proof sand paper. Three different test types were performed: monotonic strain-to-failure test, stress-relaxation test and trouser tear test. Schematic diagrams demonstrating loading directions for all test types are shown in Fig. 1(c)–(e). After being loaded onto the testing machine, all cornea specimens were sprayed with PBS prior to testing to minimize any dehydration effect.

For monotonic strain-to-failure test, specimens were divided into three groups ($n=4$ for cornea, $n=6$ for PS-4). Each group was stretched uniaxially at different extension rates: 3, 30 and 300 mm min^{-1}, until failure. Engineering stress–strain curves and corresponding elastic moduli were calculated from the linear region of recorded load–extension responses.

For stress-relaxation testing, specimens were divided into 2 groups ($n=6$ for both cornea and PS-4). Each group was strained to different extension levels (δ_0): 2 and 4 mm, in 5 s (t_r) and held at fixed displacement for 120 s (t_h). Typical load–time curve for the stress-relaxation test is shown in Fig. 2(a). The stress-relaxation response during the hold period was normalized by the peak load (P_0) and fit to the following two time-constant relaxation model using commercial nonlinear curve-fitting algorithm (Origin, Northampton, MA).

$$\frac{P(t)}{P_0} = 1 - A_1\left[1-\exp\left(\frac{-t}{\tau_1}\right)\right] - A_2\left[1-\exp\left(\frac{-t}{\tau_2}\right)\right] \quad (1)$$

where $\tau_1 < \tau_2$. This normalized function has a value of 1 at zero time and an equilibrium normalized force value $P_e/P_0 = 1 - A_1 - A_2$ (Oyen et al., 2004).

To investigate the effect of extension rate on the tear toughness of cornea, specimens were divided into three groups ($n=4$ for cornea, $n=6$ for PS-4) for the trouser tear test. Each group was stretched at different extension rates: 3, 30 and 300 mm min^{-1}. The test was stopped before the crack had fully propagated along the specimen length. Tear toughness (T) was calculated from

$$T = \frac{2P_0}{t_h} \quad (2)$$