G Model
JINJ 7516 No. of Pages 6

ARTICLE IN PRESS

Injury, Int. J. Care Injured xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Injury

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

The mechanics of corneal deformation and rupture for penetrating injury in the human eye

Andrew Rau[a,*], Scott T. Lovald[b], Steven Nissman[c], John McNulty[d], Jorge A. Ochoa[b], Michael Baldwinson[e]

[a] Exponent, Inc., 3440 Market Street, Suite 600, Philadelphia, PA 19104, USA
[b] Exponent, Inc., 149 Commonwealth Dr., Menlo Park, CA, 94025, USA
[c] Scheie Eye Institute, University of Pennsylvania Perelman School of Medicine, Philadelphia, PA, USA
[d] Google, 1600 Amphitheatre Parkway, Mountain View, CA 94043, USA
[e] Google[X], 100 Mayfield Ave., Mountain View, CA 94043, USA

ARTICLE INFO

Keywords:
Cornea
Injury
Perforation
Laceration
Rupture
Puncture
Mechanics
Penetrating eye injury

ABSTRACT

Penetrating eye injuries are surgical emergencies with guarded visual prognosis. The purpose of the current study was to determine the force required to rupture the cornea with a penetrating object, and to study how this force is affected by the object geometry. Thirty-six human cadaveric eyes from donors of various ages were characterized for diameter, axial length, and pre-test intraocular pressure. In order to investigate the effects of specimen storage time on the tissue response, half of the specimens were tested within two weeks of donor expiration, and half of the specimens were stored at −4 °C for 12–18 months. Indenters of three different diameters (1.0, 1.5, and 2.0 mm) were lowered into the apex of the cornea until rupture. Resistance to displacement (stiffness), displacement at failure, and the force at failure were determined. Multi-variable regression analysis was used to determine associations of the input variables (indenter size, test speed, and tissue postmortem time) on the mechanics of the tissue response. Twenty-nine of the 36 specimens failed at the indenter location in the cornea, four failed at the limbus, and three failed in the sclera near sites of muscle attachment. The average force at failure caused by the 1.0 mm, 1.5 mm, and 2.0 mm indenters increased from 30.5 ± 5.5 N to 40.5 ± 8.3 N to 58.2 ± 14.5 N, respectively ($p < 0.002$). The force at failure was associated with the donor age ($p < 0.001$), and globe diameter ($p < 0.041$), but was not associated with pre-test intraocular pressure, tissue postmortem time, axial length, or speed of the indenter. This study has quantified the force-displacement and failure response of a large series of human cadaveric eyes subjected to penetrating indentation loads on the cornea. The results provide useful data for characterizing the relationship between corneal rupture and the geometry of a penetrating object.

Introduction

Penetrating injuries of the eye are surgical emergencies that typically cause significant morbidity and have a guarded visual prognosis [1–3]. Blunt trauma to the eye can cause rupture at any point where the sclera is locally thinned or weakened, however, penetrating injuries often involve failure or rupture of the anterior segment. Currently, there is limited information available that describes the behavior of the cornea during large deformation and failure during penetrating injury.

The majority of the literature on corneal mechanical behavior has been limited by a focus on small strain mechanics [2,4–7], tensile strip testing, and inflation testing [8–10], and the use of non-human animal tissue [8]. The two primary methods used for measuring strain in corneal tissue are testing of cut strip specimens and inflation testing of full globes, both of which have recognized limitations. Tensile strip samples are unnaturally flattened during testing and high-strain data remains difficult to obtain due to premature failures caused by stress concentrations near the grips and imperfections at the edges of cut specimens. Inflation testing eliminates specimen gripping issues, though the method is challenged by pressure control, leakage of the pressurizing solution, and the presence of air in the solution [4]. Neither of

* Corresponding author.
E-mail address: arau@exponent.com (A. Rau).

https://doi.org/10.1016/j.injury.2017.11.037
0020-1383/

these methods has proven to be adept at measuring stress and strain in a localized region during failure.

A small number of studies have examined the risk for rupture and injury of the corneoscleral shell due to dynamic projectile loading [3,11,12]. These studies characterized eye trauma from a projectile according to projectile velocity, momentum, and energy [3]. However, this approach was unable to associate corneoscleral rupture with the mechanical state of the material; further, the basic forces, strains, and stresses required to rupture the human cornea are still not well characterized. Dynamic impact and inflation tests typically induce tissue rupture/failure away from the cornea [11,13], therefore they are not ideally suited for isolating the failure to the cornea and determining the failure properties of corneal tissue, specifically.

The aim of this study was to determine the force required to rupture the cornea with a penetrating object and to characterize the material failure properties of the corneal tissue under various loading conditions. This study relates the mechanics of perforation injury in the human eye to the geometry of penetrating objects, test rate, specimen age, intraocular pressure, and globe size. This information will provide clinicians with an understanding of the force required to penetrate the human cornea for small objects.

Materials and methods

Thirty-six human cadaveric eye specimens with known donor demographics were procured from three separate tissue foundations. Donor exclusion criteria included a history of major eye trauma and/or corneal pathology. One patient (two specimens) had a documented history of bilateral cataract surgery. Eighteen of the eyes were stored in phosphate-buffered saline (PBS) at −40 °C from 12 to 18 months prior to testing (characterized as "aged"), and eighteen eyes were procured from donors who had deceased less than two weeks prior (characterized as "non-aged") and were stored in PBS at 4 °C after harvesting. All specimens were brought to 37 °C in PBS prior to testing. Due to natural postmortem volume loss, the eyes were re-inflated immediately prior to testing by a practicing ophthalmologist via injection of PBS through the pars plana using a 30-gauge needle until physiologic pressure was reached. Pressure was measured with a Schiotz tonometer (Rudolf Riester GmbH, Jungingen, Germany, Range: 5 mmHg–60 mmHg). The axial length (in the anterior-posterior direction) and diameter (in the coronal plane) of each specimen were measured using digital calipers (Model 500-160-30, Mitutoyo, Aurora, IL). Each eye was placed inside the hemispherical recess of a Delrin® support fixture having an internal radius of 20.6 mm (13/16″) with the apex of the cornea aligned with the test axis (see Fig. 1). The fixture was rigidly attached to an 858 MiniBionix II servohydraulic load frame (MTS, Eden Prairie, MN) instrumented with a calibrated 500N capacity load cell and a calibrated displacement transducer. A hemispherical, stainless steel indenter with diameters of 1.0, 1.5, or 2.0 mm was lowered into the apex of the cornea at a constant displacement rate until failure of the specimen at the cornea, limbus, or sclera occurred. Force and displacement data were acquired at a rate of 100 Hz. Initial contact between the indenter and the cornea was determined by visual observation. An ophthalmologist who was certified by the American Board of Ophthalmology was present for all phases of the testing and examined each specimen at the conclusion of testing.

The 36 tests included three replicate tests of each test condition as shown in Table 1. The indenter was displaced at either 1.0 or 5.0 mm/s in order to determine the effect of varying speeds on failure results. A summary of the measured specimen parameters prior to testing, including donor age, globe axial length, globe diameter, and intraocular pressure are provided in Table 2. The primary outcome measures for the tests were the force at failure, displacement at failure, and overall globe stiffness. Stiffness quantifies the resistance of the globe to deformation and can be visualized as the slope of the force-displacement curve. In order to characterize the mechanics of the cornea at both low and high strains, two globe stiffnesses were determined by a linear regression fit of the load-displacement data: the low strain stiffness was calculated between displacements of 3–5 mm and the high strain stiff ness was calculated between 80%-90% of the maximum failure force. Multi-variable regression analysis was performed on the test data to determine the relationships between the input variables (indenter size, test speed, tissue post-mortem time) and the outcome measures. A p-value of 0.05 was used to indicate statistically significant differences. In order to evaluate the possibility that non-corneal failures may have affected the statistical analysis, one statistical analysis was performed using the outcomes from all tests, and a separate analysis was performed using outcomes only from specimens which failed in the cornea.

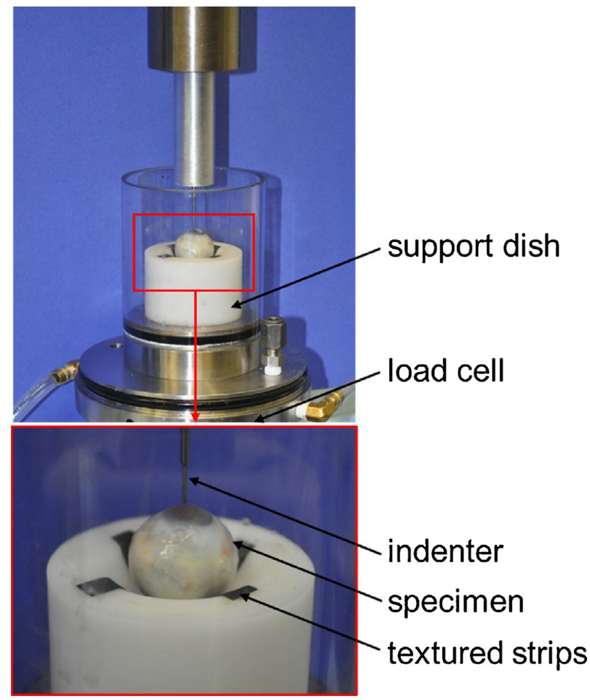

Fig. 1. Experimental set-up for human cadaveric corneal penetration testing. 11.

Results

For all three indenter sizes, the force-displacement responses exhibited an exponentially increasing force as the displacement increased (Figs. 2–4), indicating an increase in stiffness with larger displacement. Twenty-nine of the 36 specimens failed at the indenter location in the central cornea, four failed at the limbus, and three failed in the sclera near sites of muscle attachment (Fig. 5). One of the limbal failures occurred in a specimen with a history of cataract surgery. The average failure force for each indenter size increased from 30.5 ± 5.5 N (1.0 mm) to 40.5 ± 8.3 N (1.5 mm) to 58.2 ± 14.5 N (2.0 mm) as the indenter size increased (Table 3) ($p < 0.002$). For the indenter geometries examined, the coefficient of variation (St. Dev./Mean) of the failure force was less than 25%, and the coefficient of variation of the displacement at failure was less than 16%, which is indicative of reasonable experimental variability.

Table 4 includes the results of the multi-variable regression analysis which was performed on the test outcomes. For categorical variables (post-mortem time, indenter diameter, and