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Biomechanical properties of human and porcine corneas

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Abstract

The suitability of porcine corneas as approximate models for human corneas in mechanical property characterisation studies is experimentally assessed. Thirty seven human donor corneas and thirty four ex-vivo porcine corneas were tested under inflation conditions to determine their short-term stress–strain behaviour and long-term creep behaviour up to 2.8 h (10,000 s). Vertical strips extracted from further 12 human corneas and 10 porcine corneas were subjected to stress–relaxation tests for up to 20 min at different stress levels. Human and porcine corneas were observed to have almost the same form of behaviour under short and long-term loading. They both exhibited non-linear stress–strain behaviour and reacted to sustained loading in a similar fashion. However, human corneas were significantly stiffer than porcine corneas. They also crept less under long-term loading and could sustain their stress state for longer compared to porcine corneas. These differences, in addition to others identified earlier in relation to corneal mechanical anisotropy, cast doubt on the suitability of porcine corneas as models for human corneas in mechanical studies.

Keywords: corneal biomechanics; creep behaviour; stress–relaxation behaviour

1. Introduction

The transparent cornea is a most important component of the outer ocular tunic. It provides a tough protective envelope for the ocular contents and its anterior surface accounts for about 70% of the optical power of the eye (Fatt, 1978). The mechanical behaviour of the cornea, essential for maintaining its dimensional stability and hence clear vision, is dependent on the cornea's topography, thickness and the biomechanical properties of the tissue (Liu and Roberts, 2005). While topography and thickness distribution could be measured in-vivo, efforts to determine the tissue's biomechanical properties still rely on ex-vivo experiments involving human and in some cases animal corneas.

The use of animal corneas as approximate models for human corneas in mechanical property characterisation studies had been necessary because of the difficulties in obtaining human donor corneas in sufficient numbers. Several of the studies (Lombardo et al., 2006; Anderson et al., 2004a; Voorhies, 2003; Kampmeier et al., 2000; Nyquist, 1968) used porcine corneas although others (Jayasuriya et al., 2003; Hoeltzel et al., 1992; Jue and Maurice, 1986), less commonly, adopted rabbit and bovine corneas. These studies relied particularly on the comparative analysis of human and porcine corneas carried out by Zeng et al. (2001), in which rings of peripheral corneal tissue were tested using strip extensiometry to determine their short- and long-term behaviour. While porcine specimens were found to have similar short-term stress–strain behaviour to human specimens, the long-term stress–relaxation behaviour was significantly different.

The biomechanical properties that are relevant to basic understanding and numerical simulation of corneal behaviour, include the material's short-term non-linear behaviour, the change in tissue stiffness with increased intraocular pressure,

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the time-dependency of behaviour, and the degree of anisotropy. The present study aims to compare the human and porcine corneas in terms of these properties – except anisotropy which has been covered in an earlier study (Elsheikh et al., 2008) – and hence assess the suitability of the porcine cornea as a reliable model of the human cornea. The study used intact corneas subjected to posterior inflation pressures which closely represented the natural intraocular pressure. This was done in all tests except the stress–relaxation assessments in which uniaxial tests of corneal strips taken in the vertical (superior-inferior) direction were carried out.

2. Materials and methods

2.1. Specimen preparation

Forty four fresh porcine eyes from pigs aged between 4 and 6 months were obtained from a local abattoir and prepared for the experiments between two and six hours post-mortem. A central disk including the corneal button and a 2 mm scleral ring was removed with a pair of curved scissors and this was followed by the removal of the iris, lens and ciliary body. Prior to specimen preparation the central corneal thickness was measured using a pachymeter (DGH Pachmate 55; DGH Technologies, Exton, PA). The average value and standard deviation were 922 ± 81 μm.

In addition, forty nine fresh human donor corneas were obtained from the Monza Eye Bank, Monza-Milano, Italy. The corneas included a 2 mm scleral ring and all other ocular components had been removed. The specimens were unsuitable for transplantation due to low endothelial cell counts (<2000 endothelial cells/mm^2). Screening was conducted to exclude donors with central nervous system degenerative diseases, active infections and tumors of the anterior segment of the eye. The corneas were preserved in a storage medium (Eusol C; Alchima, Ponte San Nicolò, Padova, Italy) from a maximum of 12 h after death and used within 5–7 days of preservation (Naor et al., 2002). Prior to specimen preparation, the central corneal thickness was measured (using the same DGH pachymeter) and the average and standard deviation values were 572 ± 58 μm. The average value, which was about 5% higher than the average in-vivo values reported in the literature (Doughty and Zaman, 2000), indicated that Eusol C was successful in maintaining stromal hydration in spite of the low endothelial count.

2.2. Inflation tests

An inflation test rig had been built to enable subjecting human and porcine corneas to posterior pressure simulating the intraocular pressure, see Fig. 1. The rig enabled control of specimen temperature and hydration during the test, uninterrupted pressure increase or decrease to pre-selected rates, and non-contact monitoring of behaviour using digital cameras and a laser beam. Details of the rig were published in an earlier study (Elsheikh et al., 2007). The corneas were mounted onto the pressure chamber of the rig using mechanical clamps and cyano-acrylate glue to provide watertight connection along the specimens' ring of scleral tissue. The pressure chamber was filled with saline solution and connected to a small reservoir, whose vertical movement was computer-controlled to set the pressure change rate at 37.5 mmHg/min. The actual pressure in the chamber was measured using a differential pressure transducer of the FDW series (RDP Electronics, Wolverhampton, United Kingdom) and the measurements were logged automatically.

The maximum pressure applied was 170 mmHg, which was well above the normal physiological level. Three cycles of loading and unloading up to 170 mmHg were applied to condition the tissue and stabilise its behaviour before considering the results in the fourth cycle as representative of the cornea's biomechanical behaviour. The connection between the chamber and the reservoir passed through a water tank equipped with a temperature controller set at 37 °C.

A laser displacement sensor of the LK series (Keyence, Milton Keynes, United Kingdom) and two digital cameras with 8 Mb resolution positioned in the plane of the corneo-scleral intersection were used to continually monitor corneal displacement during the tests. Following the tests, mathematical shell analysis was used to derive the stress–strain behaviour of corneal material from the pressure-deformation results obtained experimentally within the fourth loading-unloading cycle (Anderson et al., 2004a,b).

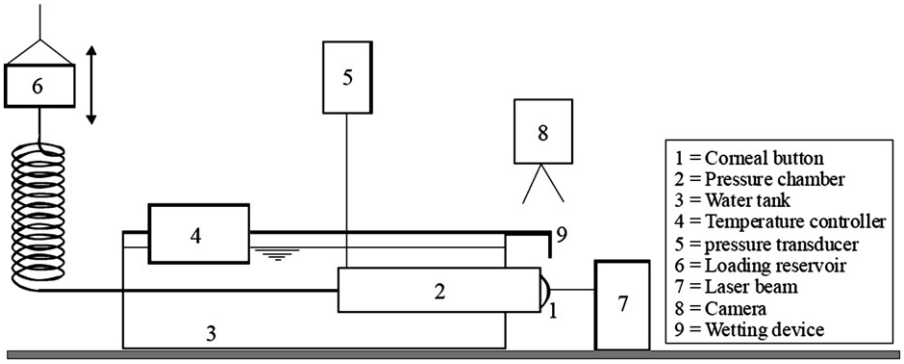

Fig. 1. Main components of inflation test rig.