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Oscillatory squeeze film analysis of soft contact lenses

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ABSTRACT

The complex modulus of a soft contact lens affects the optical performance, fitting, on-eye movement, wettability, physiological impact and overall comfort of the lens. However, despite acknowledgement that the mechanical behaviour of contact lenses is time-dependent, the rheological characteristics of contact lenses remain under-defined. While existing studies have focussed on elasticity to describe lens behaviour, this paper proposes using oscillatory squeeze film analysis to evaluate the complex modulus. The effects of excitation amplitude, repeatability and surface wetness are examined for four commercially available lenses. Slip at the lens/platen interface is considered along with bias introduced by pre-compressing the lens between platens. Test results when compared to results reported from other test methods indicate that a high degree of slip occurs at the lens platen interface suggesting that deformation is primarily due to biaxial extension.

1. Introduction

The mechanical properties of a soft contact lens are of crucial importance to the design and functionality of the lens. To be fit for purpose a lens must be both comfortable and robust; the lens must be rigid enough to allow insertion into the eye, yet flexible enough to allow comfortable on-eye movement. The ability of the lens to revert to its original shape, when placed onto the eye, is critical to its clinical performance. Should the lens be too stiff, however, serious clinical issues, such as superior epithelial arcuate lesions (SEAL), contact lens papillary conjunctivitis (CLPC) and mucin balls are known to develop [1,2]. As such, the modulus of a contact lens affects optical performance, fitting, on-eye movement, wettability, physiological impact and overall comfort [1–5].

Within the contact lens industry, the mechanical properties of soft contact lenses are typically characterised by a Young's modulus value that is often obtained via tensile testing of a lens or a strip from a lens. This parameter is a measure of stiffness and is appropriate for defining the mechanical performance in a static scenario. Alternative methods of testing, such as nanoindentation and atomic force microscopy (AFM), provide useful data but have not been adopted widely by industry and are not well suited for on-line quality control purposes.

Dynamic performance depends on the strain and the rate of strain imposed on the lens and to address this, the current study proposes a novel method for measuring the complex modulus using oscillatory squeeze film analysis. The complex modulus is a standard value used to characterise liquids and soft solids such as hydrogels that show time dependency. The nature of the time dependent behaviour of contact lenses is still a topic of debate; research practitioners are divided as to whether contact lenses exhibit behaviour that is typical of a viscoelastic or poroelastic material [1,3,6]. Essentially both material models are time-dependent, though a poroelastic model assumes that deformation of a hydrogel is governed by the disruption of flow patterns through the pores of the polymer matrix, whereas a viscoelastic model assumes it is governed by the extension and interaction of polymer chains [1,6,7]. For the purposes of this study, however, a viscoelastic model is assumed.

Dynamic testing is carried out in this study on various contact lenses using a Micro Fourier Rheometer (MFR) 2100 from GBC Scientific (used previously for analysing viscoelastic materials) [8]. The cross sectional profile of each lens type is measured so that the appropriate platen shape can be used during tests. This ensures that the lens completely fills the gap between the MFR platens thereby avoiding any stress concentrations. A squeeze force correction term is derived to account for the effects of applied pre-compression to an elastic-solid material. To assess the suitability of the oscillatory squeeze film (OSF) test method, strain amplitude, repeatability, lens type and surface wetness will be examined. Testing reveals strong evidence of slip between the surface of the lens and the platens when test results are compared to values obtained in other studies using nanoindentation and tensile testing.

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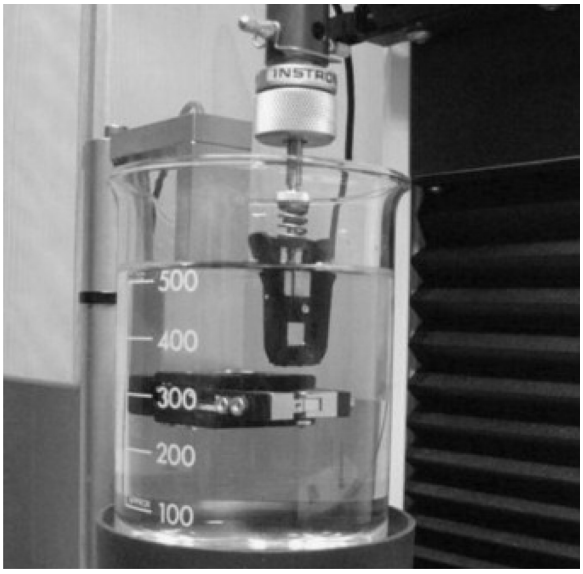

Fig. 1. Contact lens mounted in Instron 3343 tensiometer and submerged in saline solution [2].

2. Existing test methods

Due to the small size, fragile composition, and complex geometrical/mechanical properties of a contact lens, a standardised method of mechanical testing has yet to be established [5]. Common practice within the contact lens industry appears to advocate the use of tensile testing, though nanoindentation and atomic force microscopy (AFM) have also been proposed [1,9]. The method proposed here using oscillatory squeeze film analysis is well suited to the study of contact lenses. The loading regime is a combination of shear, compression and circumferential stresses which will to some extent reflect the in vivo scenario.

The level of hydration of a contact lens is also proven to have a significant effect on its mechanical behaviour [6]. Although the bulk polymer network of the lens is hydrated in an ocular environment, some water is expected to diffuse from the surface of the lens over time. This results in a surface region that may be in a transition between a 'dehydrated glassy state and a hydrated rubbery state' [3,4]. To obtain repeatable results under controlled conditions, many researchers propose mechanical testing in fully submerged conditions such as that shown in Fig. 1 [1,3,5]

At the molecular level, non cross-linked polymer chains at the lens surface extend/collapse according to the level of hydration at the surface. A chain that is exposed to air will typically rotate its non-polar methyl side towards the air, thereby decreasing the flexibility, ductility and adhesion of the lens at the surface [9]. Consequently, testing in unsubmerged conditions typically yields a higher modulus value [3], though results of previous work suggest that this is not always the case [2]. Slip at the clamp/lens interface is also likely to become an issue for a submerged lens. To reduce the likelihood of slip, the clamps must be firmly fixed to the lens, thereby increasing the pre-stress at the clamp and creating an uneven stress distribution and possible yielding. Consequently, lens hydration may account for some inconsistency in the results from mechanical testing of soft contact lenses.

The destructive preparation of strips of lens samples (as required for tensile testing) is also likely to introduce inconsistencies in the tensile test results. For instance, one study found that the length of the cut sample was found to have an effect on the lens modulus [2]. In order to improve the consistency of the test results, another study carried out tensile tests on simple flat slab shapes of the same copolymer composition [10]. Although this approach allows for more consistency in the prepared samples, it also alters the polymerisation conditions and geometry of the polymer network by comparison with formed lenses and may therefore affect results.

Unlike both tensile testing and squeeze film analysis, nanoindentation provides local mechanical measurements of the mechanical properties of the lens [1,3]. In theory, since nanoindentation is non-destructive and does not require the lens to be gripped, the inconsistencies associated with tensile testing should be mitigated. However, the major difficulty with nanoindentation is the time-dependent viscoelastic behaviour of the polymer. The elastic Oliver and Pharr model calculates the indenter-substrate contact area as a function of tip geometry and depth but not time. As such, the effects of viscoelastic creep in the unloading phase may influence results [1,6].

The complex rheology of a polymer can be characterised by dynamic mechanical analysis (DMA) – whereby a small sample of material is subjected to a cyclic stress. In this study squeeze film geometry is proposed where the lens is placed between two circular platens. The relative axial motion of the platens induces a stress in the sample and hence a force. By measuring the motion of the platens and the induced force it is then possible to determine the viscoelastic properties of the sample. Using this method the mechanical properties of a polymer may be calculated from a small volume of material over a short period of time [11]. Significantly, unlike any of the methods described above, DMA characterises both the in-phase elastic response, and the out-of-phase viscous response of the polymer.

Since the method proposed by this study is novel, little data exist from which direct comparisons may be made with the work of other squeeze film analyses. Though analyses on the rheology of PDMS (silicone) [12], and biological tissue (pig kidney) [13], allow for broad comparisons to experimental factors such as parallelism of the platens [14], inertia of the sample [15], and slip at the sample/platen interface [16].

3. Oscillatory squeeze film testing

The response behaviour of the sample under test is characterised by a squeeze force equation that is derived from the governing Navier-Stokes equations along with a series of experimental assumptions, such as; axial symmetry, linear viscoelastic behaviour and developed flow. In addition the boundary condition at the sample/platen interface strongly influences the flow profile. For the no-slip boundary condition where the sample has zero radial velocity at the platen surface, the force equation simplifies to the following equation:

$$F(\omega) = \frac{3\pi R^4}{2}\frac{z_p}{H^3}(\omega)G^*(\omega) \tag{1}$$

Where $\frac{z_p}{H^3}(\omega)$: velocity of upper platen divided by the cube of the film thickness, $G^*(\omega)$: complex modulus, R: radius of the platen. This type of flow exhibits a parabolic flow profile with a large through-lens shear gradient, resulting in a large pressure differential between the centre and edge of the platens and hence a large platen force.

By contrast if one assumes zero shear stress between the test samples and the platens, sometimes referred to as perfect slip, biaxial extension or plane strain, the force is given by:

$$F(\omega) = 3\pi R^2\frac{z_p}{H}(\omega)G^*(\omega) \tag{2}$$

Perfect slip results in a uniform flow profile with no relative velocity between the layers in the film, no shear forces and a resultant force that is much smaller than for the no-slip case [17].

The complex modulus of the sample is related to the complex viscosity $\eta^*(\omega)$ by, $G^*(\omega) = (i\omega)\eta^*(\omega)$. The complex modulus may be broken down into its real and imaginary components,

$$G^*(\omega) = G'(\omega) + iG''(\omega) \tag{3}$$

The real component $G'(\omega)$, known as the storage modulus, describes the in-phase elastic behaviour of the sample and the imaginary