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Research Paper

Mechanical performance of hydrogel contact lenses with a range of power under parallel plate compression and central load

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ABSTRACT

When a contact lens is compressed between two parallel plates (PPC) or under a central load (CLC), the constitutive relation depends not only on the mechanical properties such as elastic modulus, E, of the hydrogel materials, but also the lens power, d, or thickness variation, $h(\phi_0)$, along the meridional direction ϕ_0. Hyperopic lenses ($d>0$) are thicker at the apex along the optical axis and thin out gradually along the meridian, while myopic lenses ($d<0$) are thinnest at the apex. Mechanical deformation is quantified by the inter-relationship between applied force, F, vertical displacement of the external load, w_0, contact or dimple radius, a, and the deformed profile, $w(r)$. Force responses show that lenses with positive d are apparently stiffer in the initial loading but become more compliant as load increases. Conversely, lenses with negative d are more deformable initially and becomes gradually more resistant to loading. This is consistent with the theoretical shell model using the same E. The mechanical behavior has significant impacts in defining the degree of comfort of contact lenses as well as the lens adhesion to the corneal epithelium.

1. Introduction

Degree of comfort sensed by contact lens wearers is typically tied to the chemistry and material properties of the hydrogel, as well as the physiological aqueous environment of the eye (Nicolson and Vogt, 2001). Such conventional wisdom is justifiable when all participants in a user comfort survey wear lenses with the same shape (diopter), i.e. exactly the same geometry and thickness. Should the power of the lenses be of non-zero diopter where the spherical shell possesses thickness variation along the meridional direction as shown in Fig. 1, the mechanical response induced by an external load such as natural blinking will vary accordingly and, as we will show here, to a large extent.

Two testing methods were developed earlier to measure the materials properties of the hydrogel materials: (i) parallel

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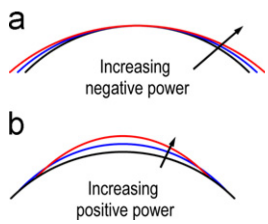

Fig. 1 – Sketch of top surface of contact lenses with different powers but the same basal curvature of the inner concave surface. The bottom curve shows $d=0$ or uniform thickness. (a) Myopic lens ($d<0$) with thinnest apical thickness and gradual thickening in the meridional direction toward rim. The apical thickness is the same for all d. (b) Hyperopic lens ($d>0$) with thickest apical thickness and gradual thinning in the meridional direction.

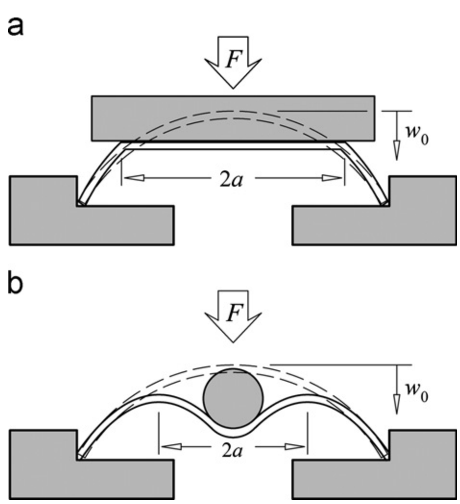

Fig. 2 – Mechanical deformation of a contact lens by (a) parallel plate compression—PPC creating a planar plate-lens contact circle with radius a, and (b) central load compression—CLC inducing a dimple with radius a. The holder has a hole along the axis to avoid hydrostatic buildup during mechanical loading.

plate compression (PPC) where the sample lens rim is freely supported by the shoulder of a circular fixture and an external load is applied via the planar surface of a cylinder, and (ii) central load compression (CLC) where external load is applied to the lens apex via a ball bearing as shown in Fig. 2. Treating the lenses as elastic shells with spherical cap geometry, a rigorous solid-mechanics model was constructed to extract the elastic modulus, E, of the hydrogel materials from force measurement (Shi et al., 2012). The model, however, was limited to lenses with uniform thickness only. In this paper, we report the mechanical characterization of lenses with a range of powers $d=-6$ to $+6$ using these two testing methods, aiming to quantify their mechanical resistance to external load. A modified model is constructed to accommodate the meridional thickness variation, $h(\phi_0)$, and will be used to analyze the new data. The changing force measurements for different d are attributed to the function of $h(\phi_0)$, since all samples are made of the same hydrogel materials assuming the same modulus.

2. Experimental

Commercially available Acuvue TruEye™ (Narafilcon-A) hydrogel contact lenses with range of powers, $d=-6$, -3, -1, $+3$, and $+6$, and rim diameter $2a=14.2$ mm were characterized. To measure $h(\phi_0)$, a 2 mm wide rectangular strip was cut diametrically from each sample, laid flat on a planar glass substrate, and was kept hydrated throughout the preparation. Optical coherence tomography (OCT) was then used to measure the film thickness as a function of off-center displacement, which was then converted into $h(\phi_0)$ using a simple geometric conversion. The exact function of $h(\phi_0)$ are trade secrets and cannot be explicitly stated here, though the average thickness is known to be roughly 100 μm. In general terms, lenses with $d<0$ have roughly the same apical thickness, but those with $d>0$ have the same rim thickness but variable thickness along the optical axis.

The detailed mechanical test protocols were discussed in a previous paper (Shi et al., 2012). All experiments were conducted using an Agilent T150 Universal Testing Machine with force and displacement resolutions of 30 nN and 10 nm, respectively. PPC was performed using an aluminum cylinder with a planar end of radius 10 mm directly attached to the load cell, while CLC was carried out using a steel ball of radius 1 mm attached to the end of a shaft. All measurements were performed in an isotonic saline solution at room temperature of 22 °C. The maximum vertical displacement or compression depth was limited to approximately $w_0=800$ μm, while the loading rate was fixed at $\upsilon=1.00$ mm min^{-1}. Buoyancy due to the progressive immersion of shaft in the liquid medium was properly subtracted from the measured force. Five lenses ($N=5$) for each power were characterized with 3 repeated loading-unloading cycles. All results reported are from representative data with one standard deviation.

3. Theory

A number of analytical models are available in the literature for nonlinear bending of shallow spherical shells with variable thickness under axisymmetric loads (Niu, 1993), but a specialized numerical routine is necessary to account for contact lens deformation. Our previous model for lenses with uniform thickness (Shi et al., 2012) is modified to accommodate for $h(\phi_0)$. A brief description of the model is given below (Fig. 3). The sample lens is a linear elastic shell of spherical cap geometry with elastic modulus, E, Poisson's ratio, υ, radius of curvature, R, thickness, $h(\phi_0)$ with meridional angle, ϕ_0. Upon external load, the shell deforms by mixed bending-stretching. The large deformation with small strain is constructed following Reissner's nonlinear shell theory (Reissner, 1950). Axisymmetry allows the two loading configurations of PPL and CLC to be governed by the same set of equations, where the elastic strain, ε, and bending moment, κ, along the