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Increased Iris-lens Contact Following Spontaneous Blinking: Mathematical Modeling

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Abstract

The purpose of this work was to study *in silico* how iris root rotation due to spontaneous blinking alters the iris contour. An axisymmetric finite-element model of the anterior segment was developed that included changes in the iris contour and the aqueous humor flow. The model geometry was based on average values of ocular dimensions. Blinking was modeled by rotating the iris root posteriorly and returning it back to the anterior. Simulations with maximum rotations of 2°, 4°, 6°, and 8° were performed. The iris-lens contact distance and the pressure difference between the posterior and anterior chambers were calculated. When the peak iris root rotation was 2°, the maximum iris-lens contact increased gradually from 0.28 to 0.34 mm within eight blinks. When the iris root was rotated 6° and 8°, the pressure difference between the posterior and anterior chambers dropped from a positive value (1.23 Pa) to negative values (−0.86 and −1.93 Pa) indicating the presence of reverse pupillary block. Apparent iris-lens contact increased with steady blinking, and the increase became more pronounced as posterior rotation increased. We conclude that repeated iris root rotation caused by blinking could maintain the iris in a posterior position under normal circumstances, which would then lead to the clinically-observed anterior drift of the iris when blinking is prevented.

Keywords

anterior chamber angle; aqueous humor; eye; finite element; glaucoma; pupillary block

Introduction

In the anterior eye, aqueous humor (henceforth “aqueous”) is secreted from the ciliary body into the posterior chamber, flows through the gap between the lens and iris into the anterior chamber, and finally drains via the trabecular meshwork. Aqueous brings oxygen and nutrients to avascular ocular tissues, notably the lens and cornea. Resistance to aqueous outflow generates intraocular pressure (IOP). A typical IOP value of 10–15 mmHg (1300–2000 Pa) is necessary for normal function of the eye (Carel et al., 1984). Increased IOP, although not a defining criterion for glaucoma (Quigley, 2005), is widely accepted as a

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Conflict of Interest

Neither of the authors has any commercial relationship that might lead to a conflict of interests.

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major risk factor (Bengtsson and Heijl, 2005; Heijl et al., 2002; Leske et al., 2003; Weinreb and Khaw, 2004).

The iris configuration can affect the IOP and has been used to classify different types of glaucoma (Foster et al., 2002; Tello et al., 2002). For example, in primary angle-closure glaucoma, the peripheral iris blocks the aqueous outflow pathway. Angle closure derives its name from the closed or narrowed angle between the anterior surface of the iris and posterior surface of the cornea.

Unlike angle closure, pigmentary glaucoma occurs when the iris is abnormally bowed towards the posterior. Although the cause of iris posterior bowing is not known for certain, “reverse pupillary block” has been proposed as a possible explanation (Karickhoff, 1993). In reverse pupillary block, a transient elevation of the pressure in the anterior chamber pushes the iris towards the posterior and pins the iris tip against the lens surface. Consequently, the aqueous flow from the anterior chamber to the posterior chamber is transiently blocked, and iris bowing is prolonged until the aqueous pressure in the anterior chamber is lower than that of the posterior chamber. Reverse pupillary block may be initiated by accommodation (Heys and Barocas, 2002; Pavlin et al., 1994; Pavlin et al., 1996) or corneoscleral indentation (Amini and Barocas, 2010).

External indentation of the cornea and/or sclera by various objects (Anderson, 1979; Bruno and Alward, 2002; Forbes, 1966; Ishikawa et al., 2000; Masselos et al., 2009; Matsunaga et al., 2004; Ritch et al., 1996; Teichmann, 1980) is known to cause opening of the anterior chamber angle, possibly via whole-globe deformation and consequent posterior rotation of the iris root (Amini and Barocas, 2009). Although no external object indents the corneoscleral surface during blinking, changes in the iris contour (Dorairaj et al., 2008; Liebmann et al., 1995) and in intraocular pressure (IOP) (Collins, 1967; Percicot et al., 1996), observed experimentally, suggest that a similar mechanism occurs. In particular, in eyes with pigmentary glaucoma (Dorairaj et al., 2008; Liebmann et al., 1995), narrow angles (Dorairaj et al., 2008), and healthy controls (Dorairaj et al., 2008), when blinking was prevented by the presence of an eye cup for ultrasound biomicroscopy (UBM) examination, the iris drifted anteriorly. Considering the similarities between blinking and corneoscleral indentation, these observations suggest that during each blink, pressure on the corneoscleral surface from the eyelids leads to iris root rotation, altering aqueous flow and iris contour.

As shown in our previous work (Amini and Barocas, 2010), due to reverse pupillary block, even an extremely short-duration (~ms) rotation of the iris root can require a long recovery time (~min); a normal individual blinks every 2–4 seconds (Karson, 1983; Sun et al., 1997). Therefore, before the iris can recover fully from one blink, a new blink occurs. We hypothesize that regular blinking prevents the full recovery of the iris-aqueous system and keeps the iris in a posterior position. Prevention of blinking would allow the iris-aqueous system to re-equilibrate and consequently would lead to the observed anterior drift of the iris. In this paper, we explore the hypothesis via a finite-element model of the anterior segment (Amini and Barocas, 2010; Heys et al., 2001; Heys and Barocas, 2002).

Methods

A finite-element model of aqueous-iris interaction was modified to simulate blinking (Table 1, Fig. 1). The governing equations and all of the boundary conditions except for the iris root rotation were identical to those discussed extensively in previous work (Amini and Barocas, 2010). Briefly, the iris was modeled as an incompressible neo-Hookean solid and the aqueous as incompressible viscous fluid. Geometry of model domain and the finite element meshes were generated using GAMBIT (Fluent Inc., Lebanon, NH) via a paving technique.

The Galerkin finite-element method was employed for spatial discretization of the mathematical model, and the implicit Euler method was used to solve the initial value problem.

We simulated each blink as 80 ms closing, no hold, and 200 ms opening, with one blink per every 3 seconds (Karson, 1983; Sun et al., 1997). The iris root was rotated posteriorly during 0.08 s using Dirichlet boundary condition. The iris root was then rotated back to the pre-blinking (non-rotated) location over 0.2 s and followed by maintaining the pre-blinking configuration for 2.72 s to complete the three-second blink period (Fig. 2). These steps were repeated over time to simulate blinking.

Since no experimental data on the exact value of iris root rotation were available in the literature, we performed a parametric study on the effect of rotation angle. We repeated the simulation for four different iris root rotation angles. The maximum iris root rotations in the four cases studied were 2°, 4°, 6°, and 8°. The largest value of the parameter (i.e. 8°) was chosen as close to the value of iris root rotation due to the corneal indentation (Amini and Barocas, 2009).

We calculated the apparent iris-lens contact and pressure difference between the anterior and posterior chambers. Apparent contact length, commonly used in UBM studies (Kanadani et al., 2006; Liebmann et al., 1995; Merula et al., 2008; Mora et al., 2010; Pavlin et al., 1992; Woo et al., 1999; Yoon et al., 2004), is defined as the distance over which there is no resolvable space between the iris and lens in the UBM image. In the computational model, we estimated the apparent contact as the distance over which the iris was at most 50µm from the lens.

Results

Figure 3 shows the iris-lens gap before blinking and immediately after the 10th blink. Before blinking, the iris-lens gap was open and aqueous flowed from the posterior to the anterior chamber (shown with an arrow in Fig. 3). As blinking continued, the iris tip became closer to the lens and the iris-lens gap narrowed. In the computational model, since the fluid domain was required to be continuous, a finite gap remained (Amini and Barocas, 2010; Heys and Barocas, 2002). Following blinking, however, the flow through the gap became negligibly small (< 2% of steady-state value).

During simulated repeated blinking, both ΔP (pressure difference between posterior and anterior chambers, Fig. 4a) and apparent iris-lens contact (Fig. 4b) stabilized after a few blinks. When the iris root was rotated 6° and 8° to the posterior, ΔP became negative, indicating higher pressure in the anterior chamber and the existence of reverse pupillary block. The parametric study (Fig. 5) showed a monotonic increase in iris-lens contact with iris rest rotation, as expected.

Discussion

Our computational model showed that apparent iris-lens contact increased following blinking as aqueous was pumped from the posterior to the anterior chamber via iris motion. When an individual is awake and conscious, spontaneous blinking occurs every 2–4 seconds (Karson, 1983; Sun et al., 1997), and the iris stays more toward the posterior. We suggest that in the absence of blinking, as in the initial condition of our model, the iris is more anteriorly located. Therefore, when blinking is prevented (Dorairaj et al., 2008; Liebmann et al., 1995), the aqueous-iris system returns to its blink-free steady-state, and the iris drifts forward.

In this study, we were not able to model globe deformation during blinking due to lack of quantitative experimental data on the effect of the ocular muscles. We expected that, similar to other cases of corneal indentation (e.g. indentation gonioscopy), the iris root would rotate to the posterior when the corneoscleral surface is pressurized by the eyelids during a blink. Parametric studies showed that regardless of how much the iris-root was rotated, the iris-lens contact increased. Based on our model, we conclude that the apparent iris-lens contact increases following prolonged blinking, but a precise estimate of the increase would require more information than is currently unavailable.

It should be noted that the elastic modulus $E = 27$ kPa in the study was based on our previous published experimental data (Heys and Barocas, 1999). In particular, Heys and Barocas (Heys and Barocas, 1999) performed mechanical testing on an incompressible bovine iris and in the radial direction. More recently, Whitcomb et al. (Whitcomb et al., 2011) calculated the instantaneous and equilibrium modulus of porcine irides using indentation mechanical testing. Instantaneous modulus of 6.0 ± 0.6 kPa and 4.0 ± 0.5 kPa and equilibrium modulus of 4.4 ± 0.9 and 2.3 ± 0.3 , were reported for posterior and anterior surface of the porcine irides. Yoo et al. (Yoo et al., 2011) also calculated the stiffness of different ocular tissues including the bovine irides using microindentation, and reported 4.86 kPa and 0.24 kPa, for instantaneous and equilibrium modulus of the bovine irides, respectively. Based on our previous work (Heys and Barocas, 2002), we would expect that varying the elastic modulus would change the pressure difference between the posterior and anterior chamber, but would have no effect on the apparent iris-lens contact and iris curvature.

A recent study using imaging of the anterior eye (Quigley et al., 2009) has proposed that the normal iris is compressible and that incompressibility of the iris (or inability of water to escape from the iris stroma) may contribute to the risk of angle narrowing or closure. In the present study, the iris was modeled as an incompressible homogeneous neo-Hookean solid, but other models could be explored.

Our model results indicate that posterior rotation of the iris every few seconds, as one might reasonably expect to occur during blinking, can induce reverse pupillary block and maintain the iris in a state of posterior bowing. When blinking is prevented, the iris can transition to a more anterior curvature over a few minutes, but upon resumption of blinking, the iris will return to the posterior configuration. All of these results are consistent with clinical observation. Our results suggest that although laser iridotomy, by allowing pressure equilibration across the iris, would lead to flattening of the iris but might not eliminate iris-lens contact, which could be driven by iris root rotation rather than by pressurization of the aqueous in the anterior chamber. That is the iris could still rub against the lens and zonules during every blink even though the rapid return to a flat contour because of the iridotomy would reduce the observable iris-lens contact to nearly zero.

Finally, it should be noted that studies have shown there are several risk factors that may contribute to pigmentary dispersion glaucoma including large eye, age, sex, and race. For example it has been shown that pigmentary glaucoma is most commonly found in young, myopic, white males (Niyadurupola and Broadway, 2008; Ritch, 1996). A relative posterior position of the iris to the lens may also contribute to pigmentary dispersion glaucoma, however, by itself does not necessarily imply the existence of pigmentary dispersion glaucoma.

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Figure 1. Anterior segment model (a, b) was created based average geometrical values for healthy individuals from published data (Table 1).

Figure 2.

Iris root angle during blinking for 6° posterior (negative) rotation. The iris was rotated towards the posterior in 0.08 s, rotated back in 0.2 s, and held for almost 2.72 s. Blinking was repeated every 3 seconds.

Figure 3.

The iris-lens gap without blinking (a) and after 10 blinks (b) simulated in the models (6° iris root rotation). When the iris-lens gap is not closed, the aqueous flows from the posterior chamber to the anterior chamber across the gap as shown schematically with an arrow.

Figure 4.

(a) ΔP , aqueous pressure difference between the posterior and the anterior chambers, and (b) apparent iris-lens contact as blinking prolongs (6° iris root rotation). The dashed lines show that the values after each blink reaches a pseudo-steady-state after a few blinks.

Figure 5.

The apparent iris-lens contact after 10 blinks when blinking was modeled using different iris root rotations (sparse bars) in comparison to the contact without blinking (solid bar).

Table 1

Mechanical and geometric parameters used in the model

Parameter	Value	Reference
Cornea radius of curvature	7.8 mm	(Pepose and Ubels, 1992)
Iris thickness	0.34 mm	(Marchini et al., 1998)
Anterior chamber diameter	12.37 mm	(Lee et al., 1984)
Anterior lens curvature	10.29 mm	(Lowe, 1972)
Lens diameter	9.0 mm	(Patterson and Delamere, 1992)
Iris-zonule distance	0.69 mm	(Marchini et al., 1998)
Iris modulus of elasticity	27 kPa	(Heys and Barocas, 1999)
Iris Poisson's ratio	0.5	(Heys and Barocas, 1999)
Aqueous humor viscosity	7.5×10^{-4} Pa.s	(Scott, 1988)
Aqueous humor density	1000 kg/m ³	(Scott, 1988)