Contribution of Different Anatomical and Physiologic Factors to Iris Contour and Anterior Chamber Angle Changes During Pupil Dilation: Theoretical Analysis

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Submitted: August 10, 2012

Accepted: February 25, 2013

Citation: Jouzdani S, Amini R, Barocas VH. Contribution of different anatomical and physiologic factors to iris contour and anterior chamber angle changes during pupil dilation: theoretical analysis. *Invest Ophthalmol Vis Sci*. 2013;54:2977–2984. DOI:10.1167/iovs.12-10748

PURPOSE. To investigate the contribution of three anatomical and physiologic factors (dilator thickness, dynamic pupillary block, and iris compressibility) to changes in iris configuration and anterior chamber angle during pupil dilation.

METHODS. A mathematical model of the anterior segment based on the average values of ocular dimensions was developed to simulate pupil dilation. To change the pupil diameter from 3.0 to 5.4 mm in 10 seconds, active dilator contraction was applied by imposing stress in the dilator region. Three sets of parameters were varied in the simulations: (1) a thin (4 μm , 1% of full thickness) versus a thick dilator (covering the full thickness iris) to quantify the effects of dilator anatomy, (2) in the presence (+PB) versus absence of pupillary block (−PB) to quantify the effect of dynamic motion of aqueous humor from the posterior to the anterior chamber, and (3) a compressible versus an incompressible iris to quantify the effects of iris volume change. Changes in the apparent iris–lens contact and angle open distance (AOD500) were calculated for each case.

RESULTS. The thin case predicted a significant increase (average 700%) in iris curvature compared with the thick case (average 70%), showing that the anatomy of dilator plays an important role in iris deformation during dilation. In the presence of pupillary block (+PB), AOD500 decreased 25% and 36% for the compressible and incompressible iris, respectively.

CONCLUSIONS. Iris bowing during dilation was driven primarily by posterior location of the dilator muscle and by dynamic pupillary block, but the effect of pupillary block was not as large as that of the dilator anatomy according to the quantified values of AOD500. Incompressibility of the iris, in contrast, had a relatively small effect on iris curvature but a large effect on AOD500; thus, we conclude that all three effects are important.

Keywords: anterior chamber angle, dilation, biomechanics, iris, pupillary block

Angle closure is well documented to be more severe in dilation.^{1,2} Three potential causes for dilation-induced angle closure, all meriting further consideration, are the following: posterior location of the dilator muscle, (dynamic) pupillary block, and iris volume change (or lack thereof). These three physiologic effects are reviewed in the subsequent paragraphs.

The dilator muscle's anatomical location and thickness affect iris configuration during dilation. In human eyes, the dilator is located on the posterior surface of the iris with a thickness of 4 to 8 μm .^{3,4} Amini et al.⁵ have recently shown that the posterior location of the dilator muscle can result in anterior bowing of the iris during dilation by a process independent of the aqueous humor (AH) dynamic pressure change. Contraction of the dilator muscle, located in the extreme posterior of the iris, tends to curl the iris and bow it to the anterior, consequently narrowing the angle.

Mapstone⁶ theorized that pupillary block arises when the resultant of the two iris internal forces, namely muscle contraction and material stretch, produces a net force acting toward the lens surface and blocking the pupil. Pupillary block

has generally been invoked in association with the steady flow of the AH through the pupil.^{7–9} Huang and Barocas,¹⁰ however, showed that steady state pupillary block is inconsistent with increased angle closure during dilation. Thus, one may naturally postulate that dilation-induced pupillary block is rather a transient phenomenon. In particular, iris motion during dilation may pressurize the AH in the posterior chamber and subsequently drive AH from the posterior to anterior chamber. If, however, internal forces (due to active contraction and tissue stretch) pin the iris tip against the lens surface and obstruct AH flow at the iris–lens gap, the pressure in the posterior chamber will rise and bow the iris to the anterior. We refer to this phenomenon as “dynamic pupillary block.” In other words, dynamic motion of the iris provides a more reasonable mechanism by which dilation could induce bowing than does the static pupillary block mechanism.

The iris volume change during dilation is another physiologic factor that may contribute to angle closure. Quigley et al.¹¹ observed a significant dynamic change in the iris volume of healthy subjects during dilation, but not in patients suffering from angle closure. They proposed the idea of iris relative

FIGURE 1. Axisymmetric model of the anterior segment showing the AH (light grey) and iris (dark grey) as well as the boundaries and dimensions of the model. AOD500 was defined as the perpendicular distance from the TM to the iris surface at a point 500 μm from the iris root.

incompressibility in angle-closure glaucoma patients. Aptel et al.¹² reported similar results for open-angle (control group) and angle-closure glaucoma patients. Quigley et al.¹¹ have argued eloquently that angle-closure glaucoma patients have less tendency to lose iris volume due to relative iris incompressibility compared with the healthy subjects. Lack of significant changes in the iris volume would cause crowding of the peripheral iris into the iris root and narrowing of the anterior chamber angle (ACA).

Thus, we consider three distinctive factors as possible contributors to the narrowing of the angle during dilation:

1. Posterior location of the dilator muscle;
2. Dynamic pupillary block and trapping of AH in the posterior chamber; and
3. Exudation/imbibition of AH by the iris stroma observed as relative incompressibility of the iris during dilation.

Each of these effects can be important, and their relative roles may vary among individuals. Because all three effects occur in every patient, it would be difficult, if not impossible, to study them in isolation via experiment. Computer simulation, in contrast, can be used to eliminate one or more factors, allowing us to assess the role of each factor independently and to quantify any positive or negative interaction among the various effects. The goal of this work was to determine, via a computational model, how each of the three factors listed above, in isolation as well as in conjunction with one or both other factors, contributes to angle closure.

METHODS

Anterior Segment Computational Model

Our previous axisymmetric computational model of the anterior segment^{10,13–16} was modified to simulate pupil dilation. The model domain representing the anterior segment was divided into the AH and iris (Fig. 1). The AH was modeled as an incompressible Newtonian fluid described using the full Navier-Stokes equations for continuity and balance of linear momentum. The iris was considered a neo-Hookean solid described by Cauchy momentum equation. The corneal axis

(Fig. 1) was the axis of symmetry in the model. The cornea, lens, trabecular meshwork (TM), ciliary body, and vitreous were modeled as rigid boundaries. The inflow and outflow boundaries for the fluid domain were considered as the ciliary body and the TM, respectively, with a volumetric flow rate of 2.5 $\mu\text{L}/\text{min}$.^{17–19} As shown in Fig. 1, the rest state of the iris was assumed to be planar with 3-mm pupil diameter.

Geometric and mechanical parameters used in model development were based on published data (Table 1). The finite element meshes were generated using GAMBIT (Fluent Inc., Lebanon, NH) via the paving technique. The Galerkin finite element method was employed to solve the mathematical equations, as described previously.¹⁵ The pressure difference between the posterior and anterior chambers, ΔP , angle open distance at 500 μm (AOD500), and apparent contact length were calculated during simulated dilation. The apparent iris-lens contact was defined by the distance over which the iris was within 50 μm from the lens. AOD500 was defined as the perpendicular distance from the TM to the iris surface at a point 500 μm from iris root (Fig. 1).

Study Design and Implementation

In order to investigate the effects of three factors, dilator thickness, dynamic pupillary block, and iris compressibility, on the iris contour and AOD500 changes during dilation, a full factorial study was undertaken with changing three parameters.

Thin Versus Thick Dilator. Two cases were considered. For the thin dilator case, the dilator was modeled as a 4- μm thick layer along the posterior iris. For the thick dilator case, the dilator occupied the entire iris thickness.

Pupillary Block Versus No Pupillary Block. The presence of pupillary block (+PB) arises naturally from the fluid structure interaction model. The absence of pupillary block (–PB) was modeled by applying an artificial force acting on iris nodes in the direction normal to the lenticular surface at the iris-lens gap (Appendix).

Incompressible Versus Compressible Iris. For the compressible iris case, the iris was modeled as a compressible neo-Hookean solid with Poisson's ratio $\nu = 0.3$, for the

TABLE 1. Geometric Parameters and Mechanical Properties of the Tissues in the Model

Parameter	Value	Reference
Cornea radius of curvature, average value	7.8 mm	Pepose et al. ²⁹
Iris thickness	0.34 mm	Marchini et al. ³⁰
Anterior chamber diameter	12.37 mm	Lee et al. ³¹
Anterior lens curvature	10.29 mm	Lowe et al. ³²
Lens diameter	9.0 mm	Patterson et al. ³³
Iris-zonule distance	0.69 mm	Marchini et al. ³⁰
Modules of elasticity of the iris	27 kPa	Heys et al. ³⁴
Aqueous humor viscosity	7.0×10^{-4} Pa.s	Scott ³⁵
Aqueous humor density	1000 kg/m ³	Scott ³⁵

The SI physical unit of viscosity is the pascal-second (Pa.s), which is equivalent to N.s/m² or kg/(m.s).

incompressible iris case, the iris was modeled as a nearly incompressible neo-Hookean solid with Poisson's ratio $\nu = 0.49$. In the compressible iris model, aqueous was assumed to flow out of the shrinking iris at a rate that preserved total anterior segment volume.

A total of eight simulations were performed to investigate the role of each factor independently and to quantify interaction among these three effects. In all simulations, the pupil diameter changed from 3.0 to 5.4 mm during 10 seconds (Fig. 2).

RESULTS

We begin by comparing briefly the anatomically realistic (thin) dilator with the unrealistic thick dilator. The thin case produced a 3- to 9-fold increase in iris curvature, depending on the other factors, whereas the thick case produced at most a 70% increase in iris curvature, a result consistent with our previous finding⁵ that the thin dilator drives curvature of the iris during dilation. Perhaps more importantly, Figure 3 shows that the thick dilator caused the iris to dilate in a pupil-blocking manner, so the elimination of pupillary block had no effect

(+PB and -PB cases nearly identical in Figs. 3A, 3B). Incompressibility of the iris led to a decrease in AOD500 for the thick dilator case (Figs. 3C, 3D), but because the result is much more pronounced in the thin case, and the thin case represents the correct anatomy, we present results only for the thin case for the remainder of this section.

Figure 4 shows the iris contour for each of the four thin cases ($\pm$ PB, incompressible versus compressible). Two effects are clear. First, the presence of pupillary block causes the iris to bow forward more, narrowing the angle. Second, the incompressible iris bulges at the iris root as the dilator muscle contracts radially, pushing the iris stroma into the angle. The combination of the two effects is seen in the lower left panel of Figure 4.

The results of Figure 4 are further quantified and analyzed in Figure 5. Examining the details of the iris contour (Fig. 5A), it can be seen that the pupillary-block effect drives curvature of the iris, and that this effect is more pronounced in the case of a compressible iris. The curvature seen in the -PB cases is attributed to the thin iris since there is no significant pressure difference across the iris. The amount of iris-lens contact (Fig. 5B, only the +PB case was considered since iris-lens contact was artificially eliminated in the -PB case) decreased slightly in the incompressible case. AOD500 decreased more (Fig. 5C) in the presence of pupillary block and for the incompressible rather than the compressible iris. The combined effect of thin dilator, +PB, and incompressible was a 36% decrease in AOD500. Finally, the anterior bowing is explained by the substantial increase in posterior-anterior pressure drop in the +PB cases (Fig. 5D).

Among all the cases, the least decrease in AOD500 and the pressure difference between posterior and anterior chambers obtained in the case of thin dilator, -PB, and compressible iris. All of the other choices (thick, incompressible, and +PB, either singly or in combination) lead to greater decrease in AOD500, that is more severe angle closure.

In the compressible case, the iris lost approximately 9% of its volume during the course of dilation. In the incompressible case, the volume loss was less than 1% (for a truly incompressible material, there would be no volume loss).

FIGURE 2. Pupil diameter versus time during dark adaptation. In all simulations, the variation of pupil diameter over time was consistent with published clinical data.^{27,28}

FIGURE 3. Mechanical response for two thick cases: (a) compressible and (b) incompressible iris in the presence of pupillary block. (c) Percent decrease of AOD500 and (d) pressure difference between the posterior and anterior chamber. In all simulations, the pupil diameter changed from 3.0 to 5.4 mm during 10 seconds.

FIGURE 4. Changes in the iris profile and anterior chamber angle for four thin cases when pupil diameter changed from 3.0 to 5.4 mm during 10 seconds. The most dramatic change in AOD500 occurred when the iris was modeled as an incompressible material, and in the presence of pupillary block (bottom left).

FIGURE 5. Thin cases. (a) Percent increase of iris curvature, (b) percent decrease of iris-lens contact, (c) percent decrease of AOD500, and (d) pressure difference between the posterior and anterior chamber. In all simulations, the pupil diameter changed from 3.0 to 5.4 mm during 10 seconds.

DISCUSSION

As summarized in Table 2, computational models of the anterior segment have been developed previously to study phenomena such as miosis, blinking, reverse pupillary block, and so on. To our knowledge, the present study was the first theoretical study

to examine the idea of dynamic pupillary block during dilation and the role of iris incompressibility in angle closure.

The changes in iris configuration and ACA associated with change in pupil diameter have been examined in several clinical studies.^{2,20} Concavity, shortening, and thickening of the iris,²¹ and, consequently, narrowing of the anterior chamber

TABLE 2. Comparison of the Theoretical Models of the Anterior Segment

Investigator	Methods		Other Information
	Aqueous Humor	Iris (Incompressible)	
Heys et al. ¹³	Transient Stokes flow	Linear elastic, passive	Mechanics of the healthy eye, iris constriction, blinking, and iris bombé were studied.
Heys and Barocas ¹⁴	Transient Stokes flow	Linear elastic, passive	Accommodation in healthy eye and pigmentary glaucoma was studied. The lens was considered as a moving rigid boundary.
Huang and Barocas ¹⁰	Steady-state Navier-Stokes flow	Nonlinear elastic, active	Pupil constriction in the healthy eye and primary angle closure glaucoma eye along with the primary angle closure glaucoma anatomical risk factors were studied.
Huang and Barocas ³⁶	Transient Navier-Stokes flow	Nonlinear elastic, passive	The accommodative micro fluctuations were studied. The lens was considered as a moving rigid boundary.
Amini and Barocas ¹⁵	Transient Navier-Stokes flow	Nonlinear elastic, passive	Corneoscleral indentation was modeled to study reverse pupillary block mechanism. The indentation was modeled by posterior rotation of the iris root.
Amini et al. ⁵	Excluded	Nonlinear elastic	Anterior bending of the iris during dilation was studied.

angle²² during dilation suggest that dilation plays an important role in angle closure pathogenesis. More recently, dynamic changes and anatomical factors related to the iris have received more attention.^{12,21,23} The purpose of this study was to create a mathematical model to simulate the dynamic motion of the iris and ACA associated with change in pupil diameter. Specifically, we studied the effects of three anatomical factors, the posterior location of the dilator, dynamic pupillary block during dilation, and iris relative compressibility.

All eight case studies showed that AOD500 decreased significantly during dilation, a result consistent with several clinical observations.^{22,23} Leung et al.²² showed that the changes of AOD500 were significantly higher in eyes with narrow angles than in those with open-angle in response to dark-light changes. Quigley et al.¹¹ and See et al.²⁴ showed that the iris loses water volume in normal individuals during dilation, but less in angle-closure patients, suggesting a relative incompressibility for angle-closure patients. Our results showed that the models with a compressible iris lost 9% of their volumes as pupil diameter changed from 3.0 to 5.4 mm during 10 seconds and had less change in AOD500 compared with models with incompressibility of the iris. The 9% volume change is smaller than the approximate 15% volume change determined via optical coherence tomography by Aptel et al.,¹² but was deemed sufficient to compare with the incompressible case. Finally, to provide a more clear presentation of the results, only the simulation predictions for $\nu = 0.3$ and $\nu = 0.49$ (explicitly referred as compressible and incompressible cases) have been included in this paper. Our studies of the intermediate values (results not presented) showed a smooth transition in AOD500 from $\nu = 0.3$ to 0.49.

When the entire thickness of the iris was simulated as the active tissue, the anterior bowing of the iris during dilation was insignificant. In the case of -PB, the presence of artificial force on the iris, prevented anterior bending of the iris and caused a slight angle-closing artifact. In the cases with a thick dilator, less change in iris curvature and, consequently, less decrease in AOD500 were seen. A thin dilator on the posterior surface of the iris caused more bending of the iris and more decrease in AOD500, suggesting the importance of the anatomy of the dilator during dilation. Amini et al.⁵ also examined iris configuration changes during dilation in the absence of AH and showed a thin layer dilator on the posterior surface of the iris resulted in more anterior bowing of the iris. It should be noted that that, in the cases with a thin dilator, the pupillary-block effect drives curvature of the iris whereas the compressibility effect drives the narrowing of AOD500.

Acknowledgments

Supported by grants from the National Institutes of Health (R01 EY15795). Computations were facilitated by a supercomputing resources grant from the University of Minnesota Supercomputing Institute for Digital Simulation and Advanced Computation, and support from the Department of Bioengineering at the University of Pittsburgh (RA).

Disclosure: S. Jouzdani, None; R. Amini, None; V.H. Barocas, None

APPENDIX

Simulation of Pupil Dilation

The iris consists of three main components: the stroma, sphincter iridis muscle, and dilator pupillae muscle. The stroma is a collagenous connective tissue whose loose nature allows AH exudation/imbibition during dilation and contrac-

tion. The activation of the two constituent muscles of the iris, the sphincter iridis, and the dilator pupillae controls the iris motion. Fibers of the dilator pupillae are aligned radially on the posterior iris surface and the sphincter muscle is located circumferentially near pupillary margin. Human pupil diameter can vary between 1.0 and 9.0 mm at maximum constriction and maximum dilation, respectively.²⁵ Since the exact contribution of the individual muscles to dilation is not clear, a simplified iris was modeled with two components: an active component (i.e., dilator) and a passive component (i.e., stroma). The dilator was localized on the posterior surface of the iris and the stroma was created on the anterior side of the iris. Pupil dilation over time (Fig. 2) was simulated by imposing an additional stress to the neo-Hookean stress along the dilator in the radial direction as defined by the following equations:

$$\sigma_{\text{dilator}} = \sigma_{\text{NH}} + \sigma_{\text{dil}}(\mathbf{e}_r \otimes \mathbf{e}_r) \quad (1)$$

where σ_{dilator} represents the stress tensor of the dilator region, σ_{NH} is the neo-Hookean Cauchy stress tensor,²⁶ $\mathbf{e}_r$ is the unit vector representing the direction of dilator muscle (i.e., radial direction), $\otimes$ represents dyadic product, and σ_{dil} is a scalar stress whose magnitude was adjusted so that the variation of pupil diameter over time was consistent with the published clinical data.^{27,28} In particular, based on Crawford's work,²⁷ the pupil diameters changed from 3.0 to 5.4 mm during 10 seconds of dilation.

Preventing Contact between Iris and Other Tissues

The iris thickness, particularly at the proximity of its root, increases as the dilation progresses. As the iris bows more anteriorly during dilation, the iris root region nearly comes into contact with the TM. Similar behavior occurs at the pupillary margin as the iris tip approaches the anterior lens surface.¹⁴ Actual contact between two smooth surfaces is impossible due to the infinite stress developed in the lubricating AH flow at the contact region. In the numerical procedure, however, the overlap of the two surfaces can lead to failure of the simulation. In order to prevent iris-TM and iris-lens overlap, artificial stresses were introduced on the iris nodes to enforce a no contact zone between the iris and lens (or TM).¹⁴

$$\mathbf{S} = A_i \cdot \mathbf{e}^{-\frac{d}{\epsilon}} (\mathbf{n}_i \otimes \mathbf{n}_i) \quad i = \text{TM and lens} \quad (2)$$

with $\mathbf{n}$ being the vector normal to the lens or TM surface at the nearest point to the surface, A and ϵ being adjustable coefficients, and d being the minimum distance from the iris to the lens or TM. The coefficient ϵ corresponded to how far the no contact zone extended into the AH, and the coefficient A corresponded to how strongly the no contact zone was enforced. The effect of the contact prevention force between the lens and iris on apparent contact was examined previously.¹⁴ Based on Heys' work,¹⁴ the values of ϵ_{lens} and A_{lens} used in all +PB studies were $0.4 \mu\text{m}$ and $5 \times 10^{10} \text{ Pa}$, respectively, to prevent overlap between the iris and the lens. -PB was modeled by applying a higher artificial stress on the iris normal to the lens by using $\epsilon_{\text{lens}} = 4.0 \mu\text{m}$ in Equation 2.

The contact prevention force depends on the distance along the iris over which the force is applied. Figure 6 shows the effect of that distance on AOD500. As shown in Figure 6, if the contact prevention force was applied over a longer distance, it had a significant impact on the active iris displacement, and AOD500. In all simulations, ϵ_{TM} and A_{TM} were set in such way that they had the minimal effect on the outcome. Based on the data in Figure 6, the maximum values of ϵ_{TM} and A_{TM} used in all studies were $16 \mu\text{m}$ and $5 \times 10^{10} \text{ Pa}$, respectively.

FIGURE 6. The effect on AOD500 of the distance over which the contact prevention force acts between the TM and iris. A significant impact on the active iris displacement was observed, when the contact prevention forces were applied over a longer distance. AOD500 was measured at the final time step of dilation. Results are based on $A_{TM} = 5 \times 10^{10}$ Pa.

Remeshing the Computational Domain

A major computational challenge was remeshing the finite element domain as the pupil diameter increased. As the iris dilated, elements along the iris-lens gap became distorted. To minimize mesh distortion, the finite element nodes were allowed to slide along the lens. As the pupil diameter continued to increase, however, much larger deformation arose, particularly near the pupil margin, which led to divergence of the solution. In order to maintain a good solution, the simulation was stopped and the fluid domain was remeshed. The steady state for new AH domain was determined assuming the iris domain was fixed. The iris solution from previous step and the new steady state solution for the new AH domain were then used to simulate the furtherance of dilation and the subsequent increase in the pupil diameter.

References

1. Lowe RF. Angle-closure, pupil dilatation, and pupil block. *Br J Ophthalmol*. 1966;50:385-389.
2. Woo EK, Pavlin CJ, Slomovic A, Taback N, Buys YM. Ultrasound biomicroscopic quantitative analysis of light-dark changes associated with pupillary block. *Am J Ophthalmol*. 1999;127:43-47.
3. Hogan MJ, Alvarado JA, Weddell JE. *Histology of the Human Eye: An Atlas and Textbook*. Philadelphia: Saunders/Elsevier; 1971.
4. Santaella RM, Destafeno JJ, Stinnett SS, Proia AD, Chang DF, Kim T. The effect of alpha1-adrenergic receptor antagonist tamsulosin (flomax) on iris dilator smooth muscle anatomy. *Ophthalmology*. 2010;117:1743-1749.
5. Amini R, Whitcomb JE, Al-Qaisi MK, et al. The posterior location of the dilator muscle induces anterior iris bowing during dilation, even in the absence of pupillary block. *Invest Ophthalmol Vis Sci*. 2012;53:1188-1194.
6. Mapstone R. Mechanics of pupil block. *Br J Ophthalmol*. 1968;52:19-25.
7. Silver DM, Quigley HA. Aqueous flow through the iris-lens channel: Estimates of differential pressure between the anterior and posterior chambers. *J Glaucoma*. 2004;13:100-107.
8. Kumar S, Acharya S, Beuerman R, Palkama A. Numerical solution of ocular fluid dynamics in a rabbit eye: parametric effects. *Ann Biomed Eng*. 2006;34:530-544.
9. Fitt AD, Gonzalez G. Fluid mechanics of the human eye: aqueous humour flow in the anterior chamber. *Bull Math Biol*. 2006;68:53-71.
10. Huang EC, Barocas VH. Active iris mechanics and pupillary block: steady-state analysis and comparison with anatomical risk factors. *Ann Biomed Eng*. 2004;32:1276-1285.
11. Quigley HA, Silver DM, Friedman DS, et al. Iris cross-sectional area decreases with pupil dilation and its dynamic behavior is a risk factor in angle closure. *J Glaucoma*. 2009;18:173-179.
12. Aptel F, Denis P. Optical coherence tomography quantitative analysis of iris volume changes after pharmacologic mydriasis. *Ophthalmology*. 2010;117:3-10.
13. Heys JJ, Barocas VH, Taravella MJ. Modeling passive mechanical interaction between aqueous humor and iris. *J Biomech Eng*. 2001;123:540-547.
14. Heys JJ, Barocas VH. Computational evaluation of the role of accommodation in pigmentary glaucoma. *Invest Ophthalmol Vis Sci*. 2002;43:700-708.
15. Amini R, Barocas VH. Reverse pupillary block slows iris contour recovery from corneoscleral indentation. *J Biomech Eng*. 2010;132:071010-6.
16. Amini R, Jouzdani S, Barocas VH. Increased iris-lens contact following spontaneous blinking: mathematical modeling. *J Biomech*. 2012;45:2293-2296.
17. Amini R, Barocas VH, Kavehpour HP, Hubschman JP. Computational simulation of altitude change-induced intraocular pressure alteration in patients with intravitreal gas bubbles. *Retina*. 2011;31:1656.
18. Toris CB, Camras CB. Measuring the outflow of aqueous humor. *Glaucoma Today*. 2007;15-22.
19. Sit AJ, Nau CB, McLaren JW, Johnson DH, Hodge D. Circadian variation of aqueous dynamics in young healthy adults. *Invest Ophthalmol Vis Sci*. 2008;49:1473-1479.
20. Liu S, Li H, Dorairaj S, et al. Assessment of scleral spur visibility with anterior segment optical coherence tomography. *J Glaucoma*. 2010;19:132.
21. Wang BS, Narayanaswamy A, Amerasinghe N, et al. Increased iris thickness and association with primary angle closure glaucoma. *Br J Ophthalmol*. 2011;95:46-50.
22. Leung CK, Cheung CY, Li H, et al. Dynamic analysis of dark-light changes of the anterior chamber angle with anterior segment OCT. *Invest Ophthalmol Vis Sci*. 2007;48:4116-4122.
23. Cheung CY, Liu S, Weinreb RN, et al. Dynamic analysis of iris configuration with anterior segment optical coherence tomography. *Invest Ophthalmol Vis Sci*. 2010;51:4040-4046.
24. See JL, Chew PT, Smith SD, et al. Changes in anterior segment morphology in response to illumination and after laser iridotomy in Asian eyes: an anterior segment OCT study. *Br J Ophthalmol*. 2007;91:1485-1489.
25. Thompson HS. The pupil. In: Hart WM, ed. *Adler's Physiology of the Eye*. Chicago, IL: Mosby-Year Book; 1992:412-441.
26. Bonet J, Wood RD. Hyperelasticity. *Nonlinear Continuum Mechanics for Finite Element Analysis*. New York, NY: Cambridge University Press; 1997:155-187.
27. Crawford BH. The dependence of pupil size upon external light stimulus under static and variable conditions. *Proc R Soc Lon. B*. 1936;121:376.
28. Reeves P. Rate of pupillary dilation and contraction. *Psychol Rev*. 1918;25:330.
29. Pepose JS, Ubels JL. The cornea. In: W. M. Hart, ed. *Adler's Physiology of the Eye: Clinical Application*. St. Louis: Mosby-Year Book; 1992:29-70.
30. Marchini G, Pagliaruso A, Toscano A, Tosi R, Brunelli C, Bonomi L. Ultrasound biomicroscopic and conventional

- ultrasonographic study of ocular dimensions in primary angle-closure glaucoma. *Ophthalmology*. 1998;105:2091-2098.
31. Lee DA, Brubaker RF, Ilstrup DM. Anterior chamber dimensions in patients with narrow angles and angle-closure glaucoma. *Arch Ophthalmol*. 1984;102:46-50.
32. Lowe RF. Anterior lens curvature: comparisons between normal eyes and those with primary angle-closure glaucoma. *Br J Ophthalmol*. 1972;56:409.
33. Patterson CA, Delamere NA. The lens. In: Hart WM, ed. *Adler's Physiology of the Eye: Clinical Application*. St. Louis: Mosby-Year Book; 1992:348-390.
34. Heys J, Barocas VH. Mechanical characterization of the bovine iris. *J Biomech*. 1999;32:999-1003.
35. Scott JA. A finite element model of heat transport in the human eye. *Phys Med Biol*. 1988;33:227-241.
36. Huang EC, Barocas VH. Accommodative microfluctuations and iris contour. *J Vis*. 2006;6:653-660.