EXTENDED REPORT

The effect of human in vivo accommodation on crystalline lens stability

Ronald A Schachar, Carlos Davila, Barbara K Pierscionek, Wickham Chen, Warren W Ward

Br J Ophthalmol 2007;91:790–793. doi: 10.1136/bjo.2006.110791

See end of article for authors' affiliations

Correspondence to:
Professor R A Schachar,
University of Texas at
Arlington, PO Box 601149,
Dallas, TX 75229, USA;
ron@2ras.com

Accepted 2 January 2007
Published Online First
10 January 2007

Aim: To determine the effect of human in vivo accommodation on the stability of the crystalline lens.

Methods: Using a dual Purkinje image (DPI) eyetracker, the phase–time difference and amplitudes of Purkinje images I (P_I) and IV (P_{IV}) were measured in 37 normal emmetropic subjects (34 women and 3 men; mean age 19.8, range 18–22 years) when they changed focus from 70 to 15 cm and simultaneously rotated their heads horizontally from side to side or made horizontal saccades between two targets 6.8° apart.

Results: When the subjects changed focus from 70 to 15 cm and rotated their heads or made eye saccades, the phase–time difference between P_I and P_{IV} decreased. During saccades, the amplitude of both P_I and P_{IV} overshoots significantly increased with focus at 15 cm; however, their ratio (P_{IV} overshoot amplitude/ P_I overshoot amplitude) significantly declined.

Conclusions: The lens is stable during accommodation. The implications of these findings on the mechanism of accommodation are discussed.

Although the changes in surface curvatures of the human crystalline lens during accommodation have been well documented and there is agreement on the central curvature changes, the stability of the lens during accommodation remains controversial. Ascertaining whether or not the lens is stable when it changes shape to accommodate is of fundamental importance for understanding the mechanism of accommodation. Instability of the lens when it is in the accommodated state suggests that the zonule is relaxed. By tracking Purkinje images I (P_I , reflection from the anterior corneal surface) and IV (P_{IV} , reflection from the posterior surface of the crystalline lens), a measure of the relative movement of the lens compared with the eye within which it is contained can be obtained for different levels of accommodative effort. Several studies have evaluated these parameters. Two of these demonstrated that the lens remains stable during accommodation,^{1,2} whereas others concluded the opposite.^{3–5} The latter studies made their conclusions from observed differences in the amplitudes of the P_{IV} overshoots as accommodation increased during saccades. One of these studies simultaneously used a dual Purkinje image (DPI) eye tracker and a scleral search coil to monitor the eye movement.³

The overshoots were observed only with P_{IV} but not with the scleral search coil. From these observations, the authors concluded that the P_{IV} overshoots were specifically associated with intraocular movements of the lens. Understanding the factors that contribute to the P_{IV} overshoots is critical when using them to draw conclusions. A more appropriate comparison, from which conclusions about lens stability could be drawn, would be that made between P_I and P_{IV} images.

If increasing zonular relaxation is associated with accommodation, the P_{IV} overshoot would be expected to have a phase–time difference when compared with that of P_I . Moreover, this phase–time difference would be anticipated to increase with further accommodative effort. This study evaluates, in young subjects, the effect of changing accommodation on the amplitudes and phase–time differences of the P_I and P_{IV} overshoots that are associated with controlled movements of the eye.

METHODS

A commercially available, calibrated and validated^{5,6} DPI eyetracker with 400 Hz bandwidth, a sample rate of 3906 Hz and a resolution >1 min of arc (Generation 6.5, Fourward Technologies, Buena Vista, Virginia, USA) was used to monitor the position of P_I and P_{IV} of the right eyes of 37 emmetropic normal subjects (34 women, 3 men; mean age 19.8 years, range 18–22 years). In addition to monitoring the horizontal movements of P_{IV} with respect to P_I in the transverse plane (x–y plane), the DPI automatically controlled the anterior and posterior movements of Purkinje image I (z-direction)—that is, the distance between the cornea and the DPI.

The left eye of each subject was patched. An eye chart was attached to a Prince rule that was suspended from the headrest of the DPI. A beam splitter (transparent to the visible spectrum and reflective to the 930 nm illumination source of the DPI) was placed between the DPI and the right eye of each subject. The subjects kept their heads in the headrest of the DPI during all measurements. P_I and P_{IV} were monitored while the subjects focused on a 20/80 Early Treatment Diabetic Retinopathy Study backlit near letter (fig 1). When the letter was either at 70 cm or at 15 cm, the subjects were instructed to simultaneously rotate their heads horizontally from side to side, for approximately 3° on each side of the midline at 5 cycles/s. This was repeated three times at each focal distance. The actual total amplitude and number of cycles/s of the subject's horizontal head rotations were determined from P_I . Differences in the amplitude and rate of the measured head rotations were statistically analysed with the t test. The mean (SD) of the difference in the time of oscillations between the maximum horizontal positions of P_I and P_{IV} of at least 15 cycles of each subject were measured.

In addition, without moving their heads, the subjects made horizontal saccadic eye movements between two 20/80 Early Treatment Diabetic Retinopathy Study backlit near letters spaced 6.8° apart when the letters were at 70 cm and at 15 cm from the cornea. For each subject and at each focal distance, the amplitudes of the forward overshoots of P_I and

Abbreviations: DPI, dual Purkinje image; P_I , Purkinje image I; P_{IV} , Purkinje image IV; UBM, ultrasound biomicroscopy

Figure 1 Schematic representation of the experimental set-up. DPI, dual Purkinje image; ETDRS, Early Treatment of Diabetic Retinopathy Study.

P_{IV} , their ratios and the phase-time differences between them were measured. For these measurements, the mean (SDs) were obtained from three saccades. All measurements were made subjectively from the computer tracings of the positions of the Purkinje images without knowledge of the subject's point of focus. One-way analysis of variance (SPSS V.13.0) was used to statistically analyse all the data.

This study adhered to the tenets of the Declaration of Helsinki, was compliant with the Healthcare Insurance Portability and Accountability Act, and was approved by the Institutional Review Board of Southern Methodist University, Dallas, Texas, USA. Written informed consent was obtained from the subjects only after the nature and possible consequences of the study were fully explained.

RESULTS

Although the mean amplitude and rate of the subjects' horizontal head rotations were different when focusing at 70 cm (3.8° (3.5°), 2.8 (0.72) cycles/s) and at 15 cm (2.8° (2.9°), 3.31 (0.96) cycles/s), with (p values <0.01), there was no difference in the angular momentum of their head rotations at the two focal distances, (p value = 0.11).

During head rotations and saccadic eye movements, P_{IV} moved synchronously with respect to P_I during accommodation (figs 2, 3). The mean phase-time difference between P_I and P_{IV} significantly decreased when the subjects changed focus from 70 to 15 cm (table 1). The decrease in phase-time when focusing at 15 cm occurred irrespective of whether the subjects oscillated their heads from side to side, with a velocity of approximately $50^\circ/s$ and accelerations of approximately $20\,000^\circ/s^2$, or whether they made horizontal eye saccades with forward overshoots of 350% (table 1).

There was no evidence of overshoots of P_I and P_{IV} during head oscillations. On the other hand, there was evidence of both P_I and P_{IV} overshoots in all eye saccades (fig 3). When the subjects changed focus from 70 to 15 cm, the mean amplitudes of the overshoots of both P_I and P_{IV} significantly increased;

however, the mean ratio of the amplitudes of the overshoots, P_{IV}/P_I , significantly decreased (table 2).

DISCUSSION

The synchrony with which P_{IV} follows P_I during head rotations implies that the lens is stable (fig 2). If the lens were unstable, there should be a significant lag in the directional change of P_{IV} with respect to P_I . These findings are consistent with the observations of Sokolowska and Thorn¹ and of Kirschkamp *et al.*² Sokolowska and Thorn objectively measured the positions of P_I and P_{IV} , accommodative amplitude and pupillary size simultaneously during accommodation.¹ They found that, for an accommodative distance of 25 cm, the lens was stable and that the tilt of the lens in the horizontal aspect was significantly decreased, whereas there was little change in vertical tilt. The conclusion reached from these observations was that there was good alignment of the lens with the pupillary axis and that this was unaltered during accommodation.¹

Using a scleral search coil and a Generation 5.5 DPI eye tracker simultaneously, each of which had a bandwidth and sampling rates approximately half of the Generation 6.5 DPI used in the present study, Deubel and Bridgeman³ observed P_{IV} overshoots. When their subjects focused at 22 cm during a 6.1° saccade, the mean P_{IV} overshoot was 1.3° . This is consistent with the present findings of a mean 1.9° P_{IV} overshoot when subjects focused at 17 cm during a 6.8° saccade.

Deubel and Bridgeman³ attributed the P_{IV} overshoots to instability of the lens as the amplitude of the P_{IV} overshoots increased with accommodation, P_{IV} overshoots were not present in the standard model eye and eye overshoots were not observed with the scleral search coil. Based on von Helmholtz's⁸ hypothesis of accommodation, they assumed that during accommodation all the zonules relaxed, which permitted the lens to oscillate more in response to a saccade, causing the amplitude of the P_{IV} overshoots to increase.

The scleral search coil is attached to the limbus, and the movement of the coil in a magnetic field identifies the position of the eye. The DPI is an optical device and depends on the reflections of the light from the surfaces of the cornea and posterior surface of the lens—that is catoptric images of the light source. As the axis of rotation of the eye is not at its centre, P_{IV} will be reflected from different parts of the posterior lens surface as the eye rotates. The posterior lens surface is flatter in its periphery than at its centre. For a specific angular rotation of a surface, the catoptric image formed by a flat surface will move faster and with greater amplitude than when formed by a concave surface. Therefore, if P_{IV} is reflected from the peripheral posterior surface of the lens, it will move faster and with greater amplitude than if it is reflected from the posterior pole. During a saccade, the eye minimally overshoots the target, as demonstrated by the approximate 0.1° overshoot of P_I (table 2). During these small eye overshoots, P_{IV} is momentarily formed from a flatter area of the peripheral posterior lens surface. This results in the appearance of the P_{IV} overshoots. The reason that both P_I and P_{IV} increased during near fixation was that the eye overshoot more at near because of the synergistic reflex of vergence and accommodation.^{9,10}

Table 1 Effect of changing focal distance from 70 to 15 cm on the mean phase-time difference between P_I and P_{IV}

	Mean (SD) phase-time difference		Significance by ANOVA
Focal distance	70 cm	15 cm	
During horizontal head rotation	27.3 (56.0) msec	20.5 (30.6) msec	0.004
During forward overshoots	5.8 (5.8) msec	3.8 (4.6) msec	0.009

ANOVA, analysis of variance.

Figure 2 Movement of Purkinje images I (P_I) and IV (P_{IV}) during horizontal head rotations while focusing at 70 cm and 15 cm.

During accommodation, the extraocular muscles are under greater tension. This would explain the increased amplitude of the overshoots during near saccades.^{9–10}

If the P_{IV} overshoots were due to lens instability, then they should be present with head oscillations. Although the angular velocity of the head rotations was slower than the overshoots, the acceleration of the eye was very similar over the time that the eye changed direction. The major difference between the two experimental paradigms was that relative central fixation was maintained during head rotations and that the eye overshoot the target during the saccades.

P_{IV} overshoots are a consequence of the eye overshooting the target during a saccade and are not due to crystalline lens instability. The crystalline lens seems to be stable during accommodation. However, photography¹¹ and ultrasound

Table 2 Effect of changing focal distance from 70 to 15 cm on the mean amplitudes of the forward overshoots of Purkinje images I and IV

	Mean (SD) amplitude		Significance by ANOVA
Focal distance	70 cm	15 cm	
P_I	0.05° (0.05°)	0.09° (0.7°)	<0.001
P_{IV}	0.99° (0.55°)	1.88° (1.01°)	<0.001
P_{IV}/P_I amplitude overshoot ratio	61.5 (82.1)	35.4 (40.1)	0.007

ANOVA, analysis of variance; P_I , Purkinje image I; P_{IV} , Purkinje image IV.

biomicroscopy (UBM)¹² have documented that the anterior and posterior zonules relax to the point of curling during human in vivo accommodation. In view of these observations and that the lens is denser than the aqueous and the vitreous humor, lens stability must be maintained by other zonules that are not readily detectable because of their small size, such as the equatorial zonules.^{13–14} The equatorial zonules have been observed in vivo with UBM.¹⁴ Unfortunately, in Ludwig *et al*'s¹² UBM study of zonular function during human in vivo accommodation, the equatorial zonules were specifically excluded because, as described in their methodology, only zonules that were at least 1 mm long were analysed.¹²

If all the zonules relax during accommodation, then gravity should affect the amplitude of accommodation. In 1962, the astronaut John Glenn did not observe a change in his near vision during his first space flight.¹⁵ Glenn was in the supine position during take-off, and was subjected to eight times the Earth's gravitational force (8 Gs). Researchers expected his vision to blur during take-off. They believed that all components of the zonule relax during accommodation, which would render the lens unstable. Since the lens is denser than the vitreous, it was expected that it would significantly shift in the posterior direction and may even dislocate during take-off because of the increased oscillations and the poor support provided by the slackened zonules. Glenn remembered a small eye chart taped to his Mercury console and the instruction to "do an emergency re-entry" if his vision blurred.¹⁵ Glenn's observation that the lens is stable and not affected by gravity, has been confirmed by measuring the accommodative amplitudes of astronauts on earth and in the microgravity environment of the space shuttle,¹⁶ and by measuring the maximum accommodative amplitude of young subjects in the supine and prone positions.¹⁷ These observations and the present study indicate that gravity and accommodation do not affect lens stability, and, coupled with the following observations, strongly suggest that the generally accepted Helmholtz' hypothesis of accommodation⁸ may be questionable:

Figure 3 Movement of P_I and P_{IV} during horizontal eye saccades while focusing either at 70 cm or at 15 cm. Note that both P_I and P_{IV} overshoot. The non-symmetry of P_I in relation to the zero baseline is due to translation of the eye and is typical of corneal image trackers.⁷

- (1) spherical aberration shifts in the negative direction during accommodation^{18–20};
- (2) the peripheral anterior lens surface flattens during accommodation^{21–24};
- (3) the posterior lens surface moves posteriorly during accommodation²⁵;
- (4) presbyopia is accompanied by a hypermetropic increase in the refractive error²⁶;
- (5) anterior disinsertion of the ciliary body to relax the zonules results in hyperopia²⁷;
- (6) the accommodative amplitude of vertebrates with spherical lenses is low and of those with “long oval” lenses is high²⁸;
- (7) equatorial traction applied to “long oval” biconvex objects results in an increase in central thickness, steepening of their central surfaces and flattening of their peripheral surfaces²⁹; and
- (8) mathematical modelling demonstrates that Helmholtz’ hypothesis requires more force and equatorial lens displacement than is physiologically and anatomically possible.^{30–32}

In summary, the crystalline lens is stable during accommodation. During a saccade the eye minimally overshoots a target, and this is greater for near than for distance vision, as demonstrated by the presence of P_I overshoots. P_{IV} overshoots are due to the momentary formation of these images from the periphery of the posterior lens surface. The stability of the lens during accommodation is opposite to the predictions of the hypothesis of Helmholtz.

ACKNOWLEDGEMENTS

We thank Elise N Schachar, Francesca Allegra and Anne Lowery for arranging for the outstanding participation of the members of Chi Omega Sorority of Southern Methodist University, Dallas, Texas, USA.

Authors’ affiliations

Ronald A Schachar, Department of Physics, University of Arlington, Arlington, Texas, USA

Carlos Davila, Wickham Chen, Department of Electrical Engineering, Southern Methodist University, Dallas, Texas, USA

Barbara K Pierscioneck, Department of Biomedical Sciences, University of Ulster, Coleraine, Northern Ireland, UK

Warren W Ward, Fourward Technologies, Buena Vista, Virginia, USA

Competing interests: RAS has a financial interest in the surgical reversal of presbyopia and WWW has a financial interest in eyetracking.

REFERENCES

- 1 Sokolowska A, Thorn F. Accommodation induced changes in crystalline lens position. *Invest Ophthalmol Vis Sci* 2003;**44**: E-Abstract, 4072.
- 2 Kirschkamp T, Dunne M, Barry JC. Phakometric measurement of ocular surface radii of curvature, axial separations and alignment in relaxed and accommodated human eyes. *Ophthalmic Physiol Optics* 2004;**24**:65–73.
- 3 Deubel H, Bridgeman B. Fourth Purkinje image signals reveal eye-lens deviations and retinal image distortions during saccades. *Vision Res* 1995;**35**:529–38.
- 4 Bailey MD, Sinnott L, Mutti DO. Oscillations of the crystalline lens following saccadic eye movements. *Invest Ophthalmol Vis Sci* 2006;**47**: E-Abstract, 5854.
- 5 Crane HD, Steele CM. Generation-V dual-Purkinje-image eyetracker. *Appl Opt* 1985;**24**:527–37.
- 6 Kording KP, Kayser C, Betsch BY, et al. Non-contact eye-tracking on cats. *J Neurosci Methods* 2001;**110**:103–11.
- 7 Crane HD. The Purkinje image eyetracker, image stabilization, and related forms of stimulus manipulation. In: Kelly DH, eds. *Visual science and engineering models and applications*. New York: Marcel-Dekker, 1994:15–89.
- 8 von Helmholtz H. Über die akkommodation des auges. *Arch Ophthalmol* 1855;**1**:1–74.
- 9 Schor CM, Lott LA, Pope D, et al. Saccades reduce latency and increase velocity of ocular accommodation. *Vision Res* 1999;**32**:3769–95.
- 10 Schor CM. Neural control of eye movements. In: Kaufman PL, Alm A, eds. *Adler’s physiology of the eye* 10th edn, St Louis: C. V. Mosby Co. 2002:830–858.
- 11 Brown N. The shape of the lens equator. *Exp Eye Res* 1974;**19**:571–6.
- 12 Ludwig K, Wegscheider E, Hoops JP, et al. In vivo imaging of the human zonular apparatus with high-resolution ultrasound biomicroscopy. *Graefes Arch Clin Exp Ophthalmol* 1999;**237**:361–71.
- 13 Farnsworth PN, Burke P. Three-dimensional architecture of the suspensory apparatus of the lens of the Rhesus monkey. *Exp Eye Res* 1977;**25**:563–76.
- 14 Schachar RA. The mechanism of accommodation and presbyopia. *Int Ophthalmol Clin* 2006;**46**:39–61.
- 15 Glenn J. Interviews with an astronaut. 2002. <http://www.stmms.org/interview.html> and http://www.space.com/missionlaunches/glenn_at_40_020225.html (accessed 6 Mar 2007).
- 16 Vanderploeg JM. Near visual acuity measurements of space shuttle crewmembers. *Aviat Space Environ Med* 1985;**57**:492.
- 17 Schachar RA, Cudmore DP. The effect of gravity on the amplitude of accommodation. *Ann Ophthalmol* 1994;**26**:65–70.
- 18 Ninomiya S, Fujikado T, Kuroda T, et al. Changes of ocular aberration with accommodation. *Am J Ophthalmol* 2002;**134**:924–6.
- 19 Hazel CA, Cox MJ, Strang NC. Wavefront aberration and its relationship to the accommodative stimulus-response function in myopic subjects. *Optom Vis Sci* 2003;**80**:151–8.
- 20 Plainis S, Ginis HS, Pallikaris A. The effect of ocular aberrations on steady-state errors of accommodative response. *J Vis* 2005;**5**:466–77.
- 21 Tscherning M. *Physiological optics*, 2nd edn. Philadelphia, PA: Keyston Publishing, 1904:160–89.
- 22 Fincham EF. Mechanism of accommodation. *Br J Ophthalmol* 1997;**8**(Suppl):2–80.
- 23 Dubbelman M, Van der Heijde GL, Weeber HA. Change in shape of the aging human crystalline lens with accommodation. *Vision Res* 2005;**45**:117–32.
- 24 Li Y, Chalta MR, Huang D. Measurement of lens curvature change during accommodation with high-speed optical coherence tomography. *Invest Ophthalmol Vis Sci* 2005;**46**: E-Abstract, 2554.
- 25 Bolz M, Prinz A, Drexler W, et al. Linear relationship of refractive and biometric lenticular changes during accommodation in emmetropic and myopic eyes. *Br J Ophthalmol* 2007;**91**:360–5.
- 26 Lee KE, Klein BE, Klein R, et al. Changes in refraction over 10 years in an adult population: the Beaver Dam Eye study. *Invest Ophthalmol Vis Sci* 2002;**43**:2566–71.
- 27 Kaufman PL, Rohen JW, Barany EH. Hyperopia and loss of accommodation following ciliary muscle disinsertion in the cynomolgus monkey: physiologic and scanning electron microscopic studies. *Invest Ophthalmol Vis Sci* 1979;**18**:665–73.
- 28 Schachar RA, Pierscioneck BK, Abolmaali A, et al. The relationship between accommodative amplitude and the ratio of central lens thickness to its equatorial diameter in vertebrate eyes. *Br J Ophthalmol*. Published Online First 31 October 2006. doi: 10.1136/bjo.2006.107524.
- 29 Schachar RA, Fygenon DK. Topographical changes of biconvex objects during equatorial traction: an analogy for accommodation of the human lens. *Br J Ophthalmol*. Published Online First 19 July 2006. doi: 10.1136/bjo.2006.094888.
- 30 Chien CH, Huang T, Schachar RA. Analysis of human crystalline lens accommodation. *J Biomech* 2006;**39**:672–80.
- 31 Abolmaali A, Schachar RA, Le T. Sensitivity study of human crystalline lens accommodation. *Comput Methods Programs Biomed* 2006;**85**:77–90.
- 32 Schachar RA, Abolmaali A, Le T. Insights into the age-related decline in the amplitude of accommodation of the human lens using a non-linear finite-element model. *Br J Ophthalmol* 2006;**90**:1304–9.