1040-5488/06/8309-0657/0 VOL. 83, NO. 9, PP. 657–665
OPTOMETRY AND VISION SCIENCE

ORIGINAL ARTICLE

Simultaneous Measurements of Refraction and A-Scan Biometry During Accommodation in Humans

LISA OSTRIN, OD, PhD, SANJEEV KASTHURIRANGAN, PhD, DOROTHY WIN-HALL, OD, and ADRIAN GLASSER, PhD, FAAO

University of Houston College of Optometry, Houston, Texas

ABSTRACT

Purpose. Accommodation is a dioptric change in power of the crystalline lens resulting from ciliary muscle contraction that leads to an increase in lens surface curvatures and thickness and changes in the position of lens surfaces. Previous studies have used A-scan ultrasound to measure changes in the position of lens surfaces with voluntary accommodation, but have not simultaneously measured the change in refraction. The goal of this study is to simultaneously measure and correlate refractive and biometric changes in the lens during voluntary accommodation in humans.

Methods. Refraction was measured off-axis in the right eye and biometry on-axis in the left eye simultaneously during voluntary accommodation in 22 human subjects between the ages of 21 and 30 years (mean ± standard deviation: 25.8 ± 2.3 years). Subjects viewed a distant target and four near targets spanning the full accommodative range available to evaluate refraction and lens surface position at each accommodative state.

Results. Maximum objectively measured accommodative amplitude of all subjects was 5.64 ± 0.21 D (mean ± standard error of mean). Biometric and refractive changes during accommodation were linearly correlated. The mean ± standard error of mean decrease in anterior chamber depth was 0.051 ± 0.008 mm/D, increase in lens thickness was 0.067 ± 0.008 mm/D, and increase in anterior segment length was 0.017 ± 0.005 mm/D during accommodation. There was a net anterior movement of the lens center of 0.017 ± 0.005 mm/D.

Conclusion. Anterior chamber depth, lens thickness, and anterior segment length change linearly with refraction during accommodation. Per-diopter changes in the lens were greater in the current study compared with previous studies in which only accommodative demand was measured, which overestimates the accommodative response.

(Optom Vis Sci 2006;83:657–665)

Key Words: A-scan biometry, lens thickness, anterior chamber depth, voluntary accommodation, accommodative mechanism

Accommodation is defined as a dioptric change in the optical power of the eye brought about by ciliary muscle contraction.[1] Accommodation occurs with an effort to focus on a proximal or blurred target or with instillation of a parasympathomimetic agent. Accommodative optical change is brought about by an increase in curvature of the crystalline lens surfaces, an increase in lens thickness, and a decrease in lens equatorial diameter.[2–8] Amplitude of accommodation decreases gradually throughout life, resulting in presbyopia.[9–11] Understanding optical and biometric changes in the lens is important for understanding the mechanism of accommodation and age-related changes leading to presbyopia.

Anterior segment biometry can be measured during accommodation to determine biometric changes that lead to refractive change. In vivo ocular biometry, including anterior chamber depth (ACD), lens thickness (LT), and anterior segment length (ASL), i.e., cornea to posterior lens surface, can be measured with Scheimpflug photography, partial coherence interferometry (PCI), ultrasound biomicroscopy, and A-scan ultrasonography (Table 1). Several investigators have demonstrated an anterior movement of the anterior lens surface during accommodation.[3,7,12–20] Movements of the posterior lens surface during accommodation are less clear, and variation exists between studies as well as within studies,

TABLE 1.
Changes in anterior segment biometry (mm/D) during voluntary accommodation from various human studies[a]

Study	Method of Measuring Biometry	Method of Measuring Accommodation	Change in ACD/D	Change in LT/D	Change in ASL/D
Current study	A-scan	Refraction measured *objectively* simultaneously in the contralateral eye	−0.051 ± 0.008	+0.067 ± 0.008	+0.017 ± 0.005
Current study	A-scan	Maximum *subjectively* measured accommodative amplitude	−0.044	+0.055	+0.010
Drexler et al.[11]	PCI	Accommodative demand	−0.025	+0.034	N/A
Koeppl et al.[18]	PCI	Accommodative demand *(young subjects)*	−0.043	+0.043	0.00
Koretz et al.[16]	Scheimpflug	Refraction measured consecutively	−0.037	+0.043	+0.003
Dubbelman et al.[7]	Scheimpflug	Accommodative demand	Age-dependent: −0.036 to −0.040[b]	+0.045	+0.008
Patnaik[23]	Photographic	Accommodative demand	−0.044	N/A	+0.011
Garner et al.[31]	A-scan	Refraction measured consecutively	−0.031	+0.036	N/A
Kirschkamp et al.[19]	A-scan	Calculated from phacometry and A-scan	−0.054	+0.054	N/A
Shum et al.[13]	A-scan	Accommodative demand	−0.033 to -0.04	+0.053	N/A

[a]Values for the current study represent mean ± standard error of mean.
[b]For ages comparable to this study.
ACD/D, anterior chamber depth (in millimeters) per diopter; LT/D, lens thickness (in millimeters) per diopter; ASL/D, anterior segment length (in millimeters) per diopter; PCI, partial coherence interferometry; N/A, not available.

having been reported to move anteriorly,[13,17,21,22] stay in the same position,[19,21,23] and move posteriorly.[7,12,18,21,24]

Previous studies have measured changes in anterior segment biometry during voluntary accommodation in humans, but correlated these changes with accommodative stimulus demand as opposed to accommodative response.[7,12,25] When the data for one subject, measured with PCI, were replotted as a function of the stimulus demand, lens movements per diopter were nonlinear.[12,26] The accommodative response is typically less than the demand resulting from inherent depth of focus of the eye, resulting in a lag of accommodation.[27–29] The accommodative stimulus response function generally demonstrates a lead for stimuli <1 D and a lag for stimuli >1 D. Maximum accommodative amplitude estimated by subjective reports of target clarity overestimate the objectively measured maximum accommodative amplitude.[10,11,16,30,31] Therefore, changes in anterior chamber depth and lens thickness per diopter of accommodation are likely to be underestimated when compared with stimulus demand and become nonlinear at high accommodative demands.

In a study in humans, biometric changes were measured and correlated with the accommodative response to a 4-D accommodative demand, which was calculated using phacometric and optical vergence measurements.[20] Only one accommodative state was measured, so no information about the linearity of the response is available. Another study measured biometry at four accommodative demands,[32] but the accommodative response was measured subsequent to biometry for the same accommodative stimulus amplitudes, which assumes the eye accommodates the same amount during biometry and subsequently during refraction measurements. Consecutive rather than simultaneous measurements of refraction and biometry may introduce variations, especially considering the very different conditions required for visualization of the stimulus with the contralateral eye during applanation A-scan versus noncontact refraction measurements. Similarly, Scheimpflug photography has been used to measure biometry at several accommodative states followed by refraction measurements with a Hartinger coincidence refractometer.[17] The standard deviations of the measurements were large relative to the means, which may be the result of subsequent rather than simultaneous measurements of biometry and refraction.

Anterior segment biometry has also been measured during pharmacologically stimulated accommodation in humans.[19,21,33] Pharmacologic stimulation of accommodation results in a dramatic, concurrent pupil constriction resulting in a 1- to 2-mm pupil diameter after 25 minutes.[11] This can make objective measurement of accommodation difficult or impossible without a refractometer capable of measuring through such small pupils and can cause a significant overestimation of accommodative amplitude when measured subjectively as a result of an increase in depth of field from the small pupils.[11,33]

Pharmacologically stimulated ocular accommodative biometric changes differ from those induced by voluntary accommodation in humans[13,19] and Edinger-Westphal stimulated accommodation in monkeys.[34] Pharmacologic stimulation in monkeys initially results in an increase in lens thickness and anterior movement of the anterior lens surface but with a subsequent anterior movement of the entire lens that is not seen with voluntary or Edinger-Westphal-stimulated accommodation. This has also been demonstrated in young[13,21] and presbyopic[19,22] human subjects. The pharmacologically induced anterior movement of the entire lens may further contribute to the refractive change.

In anesthetized rhesus monkeys, ocular biometry has been measured during accommodation with continuous ultrasound biometry,[26,34] clinical A-scan ultrasonography,[35] and Scheimpflug photography.[23] Accommodation was stimulated through a permanent electrode in the Edinger-Westphal nucleus of the midbrain, and refraction was measured objectively. These studies show that changes in anterior segment biometry are linearly correlated with changes in refraction over the full range of the accommodative response.

Here, a clinical A-scan ultrasound instrument is used in young, prepresbyopic humans to measure lens biometric changes in one eye while simultaneously measuring changes in refraction in the contralateral eye for various accommodative states. Information about accommodative biometric changes in the normal phakic eye will lead to a further understanding of how the eye undergoes accommodative changes.

METHODS

Twenty-two subjects (10 male and 12 female), ages 21 to 30 years (mean ± standard deviation [SD], 25.8 ± 2.3) participated. The study followed the tenets of the Declaration of Helsinki and was performed in accordance with an institutionally approved human subjects protocol with full informed consent from the participants. All subjects were in good physical and ocular health and completed a questionnaire to ascertain any contraindications to participation. Exclusion criteria included astigmatism >2.00 D, amblyopia (best corrected vision <20/30 in one eye), prior ocular surgeries, ocular disease, and known sensitivities or contraindications to proparacaine.

All subjects were correctable to 20/20 distance acuity, and subjects with refractive errors greater than ± 0.50 D were corrected with contact lenses. Seventeen subjects were corrected with soft contact lenses, two with rigid gas-permeable contact lenses, and three required no correction. Spherical equivalent refractive errors, determined from an eye examination within the prior year, for the right eyes ranged from +0.75 to −6.00 D (mean ± SD, −2.53 ± 1.98 D) and for the left eyes ranged from +2.75 to −5.75 D (mean ± SD, −2.52 ± 2.19 D). Subjects included 18 myopes (−0.75 to −6.00 D), three emmetropes (± 0.50 D), and one hyperope (+2.75 D).

Subjective accommodative amplitude was first measured monocularly in each eye with the pushup test while the other eye was occluded. Subjects wore their distance corrections and were instructed to focus on 0.37-M letters of a near reading card at 50 cm. The chart was slowly brought closer to the eye until they reported first sustained blur. The reciprocal of three averaged near reading distances was recorded as the subjective accommodative amplitude for each eye.

The left eye was then occluded and distance refraction was measured in the right eye with a Hartinger coincidence refractometer (HCR; Zeiss, Jena, Germany),[36] which measured the spherical refraction in the horizontal meridian. The subject viewed a distant letter target at 20 feet with the right eye as seen reflected off a beam splitter mounted at 45° immediately in front of the HCR. Three measurements were recorded and averaged.

Accommodative amplitude was then measured objectively in the right eye with the HCR. The left eye was occluded, and the right eye viewed a near letter target reflected off the beam splitter. The subject was instructed to focus on the near target as it was slowly moved toward the eye on a track. The examiner continuously adjusted the mires of the HCR to neutralize the refraction as the eye accommodated until no further change in refraction was observed. The average of three dioptric differences between the most myopic-accommodated refraction observed and the distance refraction was recorded as the objectively measured accommodative amplitude.

The following approach was used to measure A-scan biometry in the left eye using a standard clinical A-scan ultrasound instrument (model A-5500; Sonomed, Lake Success, NY) set in applanation mode and refraction simultaneously in the right eye using the HCR. The subject sat with their head in the HCR chinrest. The right eye had a contact lens correction in place, if necessary, and the left eye was uncorrected. One drop of proparacaine 0.5% was instilled into the left eye. The left eye viewed past the side of the HCR at a laser fixation spot on the wall at approximately 1 meter to maintain primary gaze position. The right eye focused on the far or near targets reflected off the 45° angled beam splitter in front of the HCR. The distant letter chart, viewed reflected off the beam splitter by the right eye, was positioned so that one of the letters on the chart was seen by the subject superimposed with the laser fixation spot viewed by the left eye. Five A-scan measurements were then made in the left eye while the right eye maintained fixation on the letter on the distant letter chart. The laser fixation spot was not a stimulus to accommodate because it was not visible during the A-scan measurements because the transducer obscured the left eye. Distance refraction was measured in the right eye by one examiner with the HCR as A-scan biometry was simultaneously measured in the left eye by a second examiner. The target was then moved on the track closer to the subject's right eye until the maximum accommodative refractive change was achieved. The distance from the eye to the target was measured. As the target was moved closer to the right eye, alignment of the right eye with the HCR axis was maintained, but the left eye had a strong accommodative convergence response. The A-scan measurement could not be made in the left eye in this convergent posture as a result of the proximity of the side of the HCR. The left eye was returned to the primary gaze position to again fixate on the laser spot by changing the angle of the near target viewed by the right eye to cause the right eye to take on the convergence posture (Fig. 1). The result was that the right eye was converged, the relative vergence between the two eyes was maintained, both eyes were accommodated, the right eye viewed the near target reflected off the beam splitter, and the left eye was in primary gaze position, aligned with the laser fixation spot. The near chart viewed by the right eye was therefore superimposed with the fixation spot seen with the left eye. The subject was then asked to attend to and focus on the near letter chart with the right eye. One drop of proparacaine was instilled into the left eye, and five A-scan measurements were made in the left eye by one examiner while three refraction measurements were simultaneously made in the right eye by the second examiner.

Three intermediate target distances between the far target and the near target position that produced maximum accommodation were chosen for each subject. These distances were chosen by dividing the maximum objectively measured accommodative amplitude by four to obtain three equally spaced accommodative states within the range of accommodative amplitude available in each subject. The near target was placed on the track perpendicular to the line of sight at the subject's near point and was then moved away from the subject while measuring the refraction with the HCR until the desired accommodative state was achieved. The refraction of the right eye was measured three times with the target at this position, along the optical axis of the right eye and with the laser fixation spot off, and the distance from the eye to the target was noted. The angle of the near target was then changed, maintaining the same distance from the eye until all accommodative convergence was taken up by the right eye, and the left eye was returned to view the laser spot in the primary gaze position superimposed on the near target seen off-axis with the right eye. A-scan biometry was measured five times in the left eye while refraction was measured simultaneously three times in the right eye. This procedure was repeated for each of the two other intermediate distances. Proparacaine was instilled as needed in the left eye. This resulted in simultaneous left eye A-scan and right eye refraction measurements at the far point, the near point, and three intermediate accommodative states for each subject. To ascertain if there is any systematic error resulting from the off-axis refraction measurements, refraction was also measured in the right eye for the same target distances while the right eye was in an on-axis posture and the on-axis and off-axis measurements were compared.

For each A-scan measurement, ACD, LT, vitreous chamber depth, and axial length were measured. Anterior segment length was determined by adding ACD and LT. The A-scan ultrasound instrument was set to a sound velocity of 1548 m/s. All data were recalculated using accepted sound velocities of 1532 m/s for the anterior and vitreous chambers and 1641 m/s for the lens,[37–39] and the raw data were not considered further. A single velocity was used for the lens as is typically done[18,20,35] despite a possible gradient of velocity in the lens cortex and nucleus.[40]

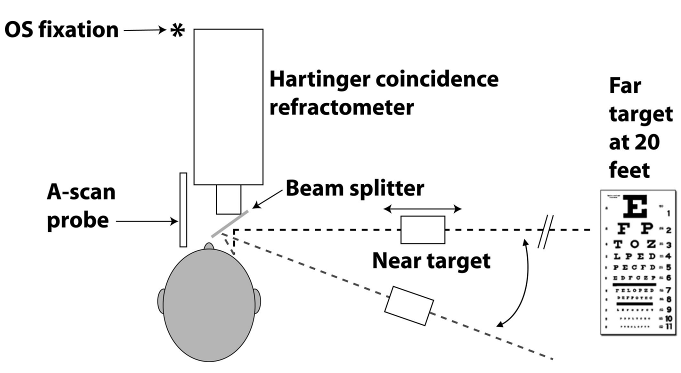

FIGURE 1.
Experimental setup. Refraction was measured with a Hartinger coincidence refractometer off-axis in the converging right eye as the right eye viewed the target reflected off the beam splitter. A-scan biometry was measured simultaneously on-axis in the left eye after the fixation target seen by the left eye had been visually aligned with the letter target seen by the right eye.

RESULTS

Subjectively measured maximum accommodative amplitude for right eyes was 7.7 ± 0.33 D (all values, mean ± standard error of mean [SEM]) and for left eyes was 7.8 ± 0.31 D. Maximum objectively measured accommodative amplitude for all right eyes was 5.64 ± 0.21 D, measured off-axis at the time the A-scan measurements were being made in the left eye. Subjectively measured accommodative amplitude was significantly greater than objectively measured accommodative amplitude (paired t test: $p < 0.0001$, df = 21).

On- and off-axis accommodation in the right eye, measured with the HCR, was not systematically different for the same target distances (Fig. 2A). On- and off-axis refraction measurements were well correlated with $r^2 = 0.921$. An orthogonal regression fit to the data has a slope of 1.03 and y-intercept of 0.28. Bland-Altman analysis was performed, which compares two measurement techniques, both of which have an associated error comparable to each other.[41] This analysis shows that the two measurements are comparable to each other without systematic differences, having a mean difference of -0.17 ± 0.06 D and a 95% confidence interval of ± 1.1 D (Fig. 2B).

Axial length in the left eye was significantly linearly correlated with distance refractive error in the right eye (Fig. 3). For emmetropes with refractive errors within ± 0.50 D (n = 3), axial length was 23.86 ± 0.41 mm. For every diopter of refractive error, axial length increased (myopes) or decreased (hyperopes) on average by 0.36 ± 0.08 mm/D.

During accommodation, there was an increase in lens thickness with an overall anterior movement of the lens anterior surface and a posterior movement of the posterior surface (Fig. 4). Biometric changes in the lens surface positions were linearly correlated with contralateral changes in refraction (mean ± SEM and p for slope significantly different from 0 given below). Linear regression analysis shows that anterior chamber depth decreased 0.051 ± 0.008 mm/D ($p < 0.0001$, Fig. 5A), lens thickness increased 0.067 ±

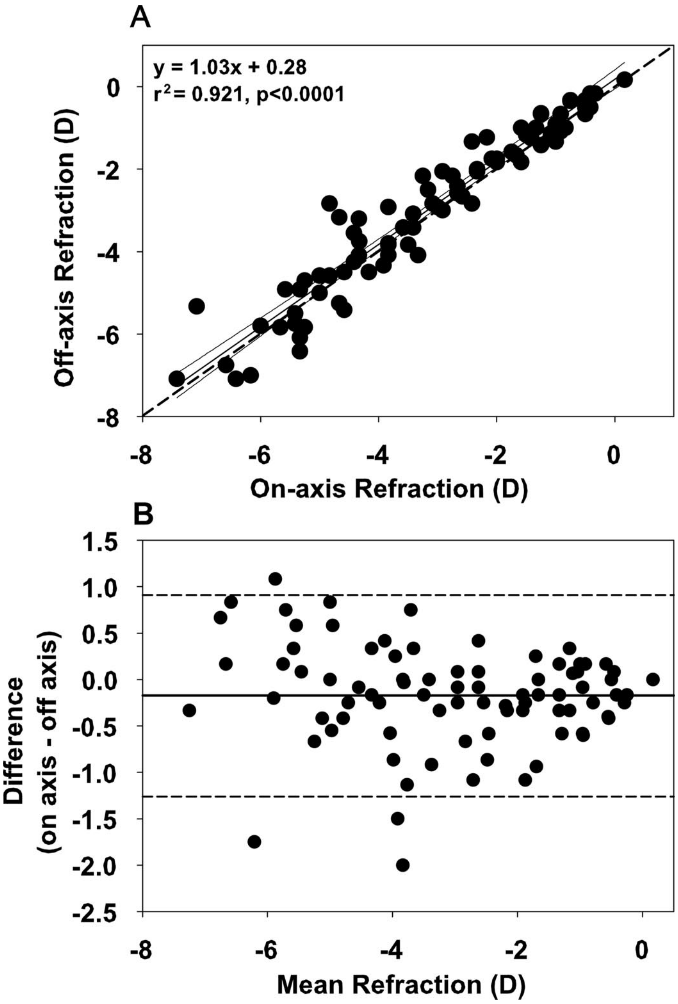

FIGURE 2.

(A) Off-axis refraction was not systematically different from on-axis refraction. The equation shown is for the orthogonal regression with the 95% confidence interval shown. The dashed line is the 1:1 line and is within the 95% confidence interval of the regression line. Each data point represents an average of three measurements for a given accommodative state, with an average standard deviation of 0.13 D for on-axis measurements and 0.17 D for off-axis measurements. (B) Bland-Altman analysis results in a mean difference of 0.17 ± 0.06 D with a 95% confidence interval of ± 1.1 D.

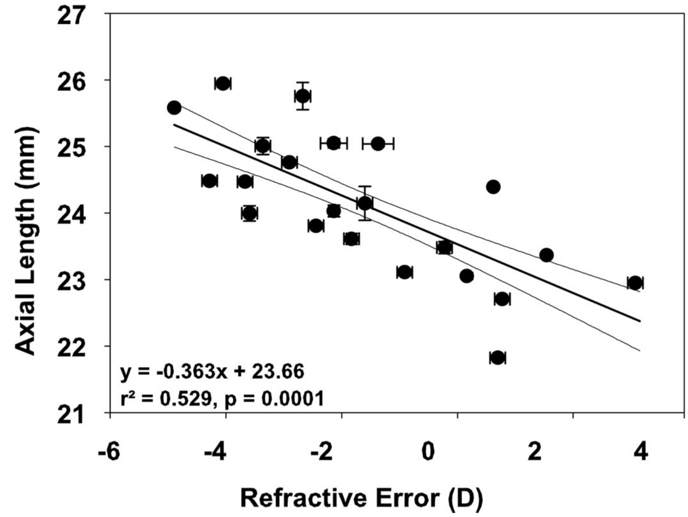

FIGURE 3.

Axial length is linearly correlated with refractive error with a change in axial length of 0.36 mm for every diopter of refractive error (n = 22). Error bars represent the standard deviation (SD) of an average of five A-scan measurements (average SD, 0.126 mm) and three refraction measurements (average SD, 0.17 D). Ninety-five percent confidence interval for the regression line is shown.

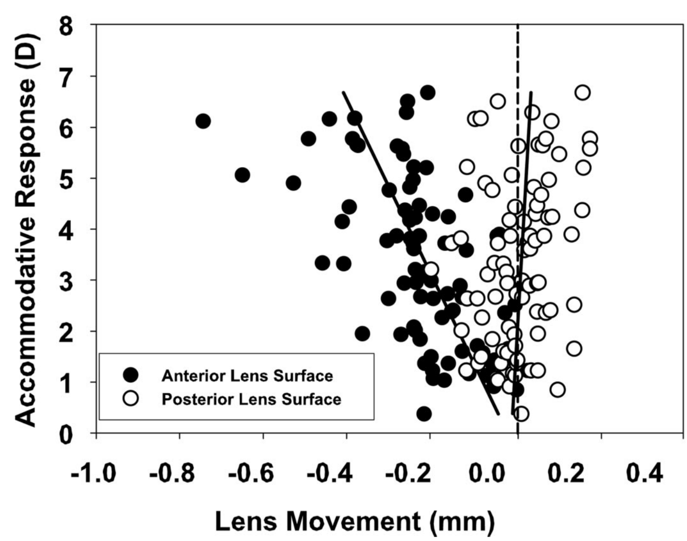

FIGURE 4.

With accommodation measured in the right eye, there is an anterior movement of the anterior lens surface (negative values, $p < 0.0001$) and a posterior movement of the posterior lens surface (positive values, $p < 0.01$) as measured in the left eye (n = 22). Linear regression lines fit to the data are the same as those shown in Figure 5. Each point represents an average of three refraction (average standard deviation [SD], 0.17 D) and five A-scan measurements (average SD for anterior lens surface = 0.135 mm; posterior lens surface = 0.132 mm).

0.008 mm/D ($p < 0.0001$, Fig. 5B), and anterior segment length (anterior chamber depth plus lens thickness) increased 0.017 ± 0.005 mm/D ($p < 0.01$, Fig. 5C). The lens center (ACD+LT/2) moved anteriorly 0.017 ± 0.005 mm/D ($p < 0.01$, Fig. 5D). The change in lens thickness per diopter of accommodation for each individual was not significantly correlated with the accommodative response of the eye indicating that the ratio of the change in thickness to the accommodative response is the same for the first diopter and the last diopter of accommodation. There was a 2.1% increase in lens thickness per diopter of accommodation from rest. On average, 75% of the increase in axial lens thickness during accommodation can be accounted for by an anterior movement of the anterior lens surface, and 25% of the increase in lens thickness is the result of a posterior movement of the posterior lens surface. Overall, there was a 10.47% increase in lens thickness in the left eye for a maximum of 5.64 ± 0.21 D of accommodation in the right eye.

For the maximum objectively measured accommodative amplitude of 5.64 D, the lens anterior surface moved anteriorly by 0.34 ± 0.03 mm, lens thickness increased by 0.42 ± 0.04 mm, and the posterior lens surface moved posteriorly by 0.08 ± 0.02 mm. For 9% of subjects (n = 2), there was less than ± 0.02-mm movement of the posterior lens surface during maximum accommodation. Eighteen percent of subjects (n = 4) had an anterior movement of the lens posterior surface of 0.05 to 0.08 mm, and 73% of subjects

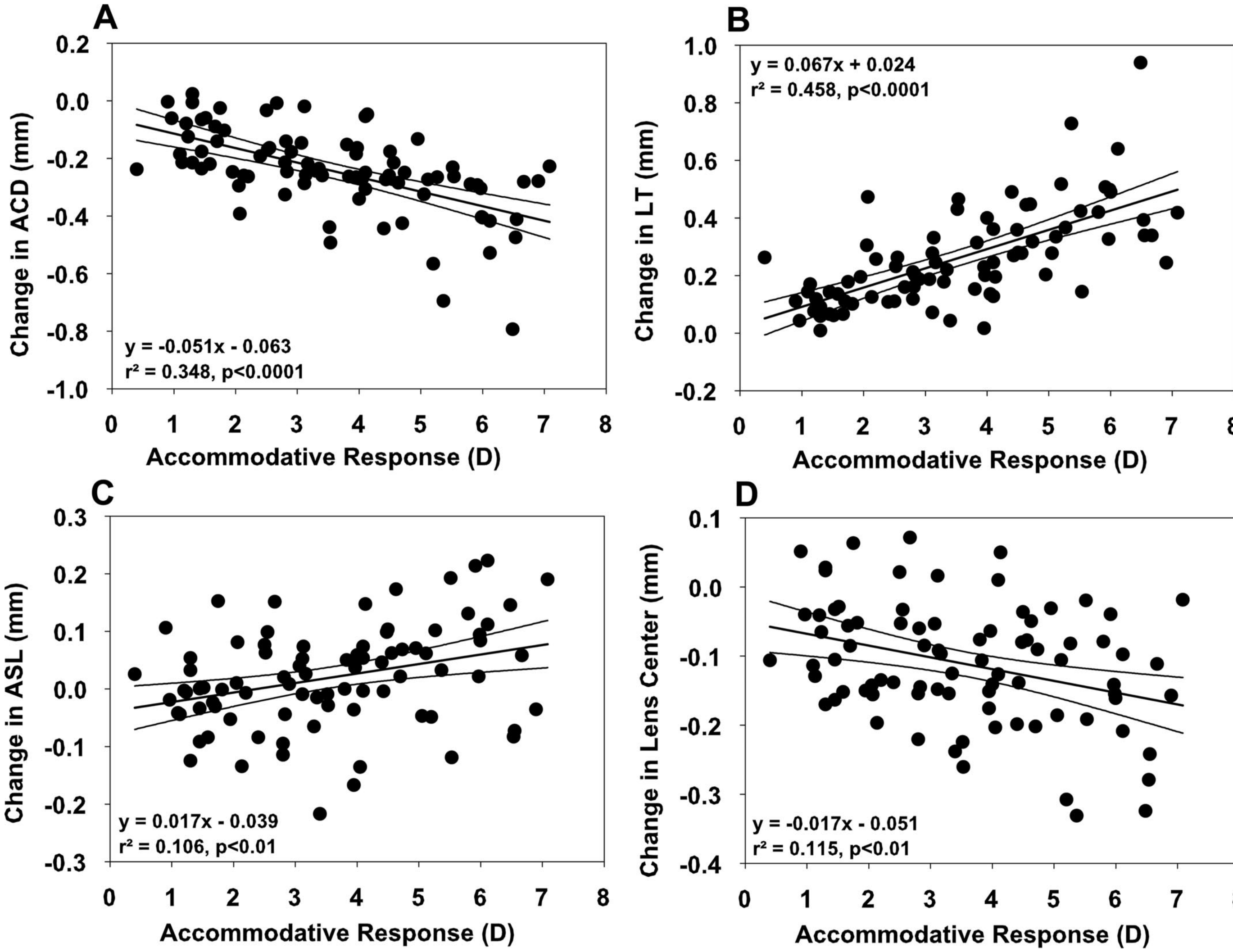

FIGURE 5.

With accommodation measured in the right eye, there is (A) a decrease in anterior chamber depth, (B) an increase in lens thickness, (C) an increase in anterior segment length, and (D) an anterior movement of the lens center in the left eye (n = 22). Each point represents an average of three refraction (average standard deviation [SD], 0.17 D) and five A-scan measurements (average SD for anterior chamber depth = 0.135 mm; lens thickness = 0.115 mm; anterior segment length = 0.132 mm; lens center = 0.122 mm). Ninety-five percent confidence intervals for the regression lines are shown.

(n = 16) had a posterior movement of the lens posterior surface of 0.02 to 0.22 during maximum accommodation. Although changes in anterior chamber depth occur linearly with change in lens thickness, the slope of -0.82 is significantly different from -1.0 ($p < 0.0001$), indicating that the change in lens posterior surface position accounts for some change in lens thickness. Interindividual variation in the change in lens thickness per diopter of accommodation was not correlated with refractive error, baseline lens thickness, or maximum accommodative amplitude ($p = 0.80$, $p = 0.43$, and $p = 0.62$, respectively, data not shown).

If changes in biometry are compared with the subjectively measured accommodative amplitude (7.7 D), as opposed to the objectively measured accommodative amplitude (5.64 D), the per-diopter changes are smaller. Anterior chamber depth would decrease 0.044 mm/D, lens thickness would increase 0.055 mm/D, and anterior segment length would increase 0.010 mm/D.

DISCUSSION

In this study, refraction in the right eye and anterior segment biometry in the left eye were measured simultaneously during voluntary accommodation in young humans. A linear relationship between refraction and biometry was found during accommodation for all subjects with the anterior lens surface moving anteriorly and the posterior lens surface moving posteriorly as the accommodated refraction became more myopic.

The accommodative refractive and biometric changes have not previously been measured simultaneously in the same eye with commercially available clinical instrumentation. The near triad of accommodation, convergence, and pupil constriction is bilaterally and neuronally coupled in the brain. Previous studies have shown that the accommodative response between the two eyes is equivalent,[42,43] especially when the stimulus is presented monocularly.[44,45] This allows stimulation of accommodation in one eye and measurement of accommodation-related biometric changes in the other eye. Although two subjects had anisometropic refractions (2-D and 0.75-D difference between eyes, respectively), ocular refraction and axial length between the two eyes were significantly correlated for all subjects (Fig. 3). The subjects were comprised of individuals with a range of refractive errors, including a large number of myopes. Myopes are known to have a larger accommodative lag compared with emmetropes.[46] However, in this study, the accommodative refractive change was measured with a refractometer and the corresponding biometric changes were measured with A-scan ultrasound. Therefore, by measuring the actual refractive and biometric changes, the issue of a lag of accommodation is avoided. Similarly, because the optical and biometric changes were compared, small errors in refractive corrections and changes in target size and luminance with target distance are irrelevant. It is possible that using subjects with a range of refractive errors, including myopes with an unknown etiology (stable versus progressing, early versus late onset), may have induced greater variability in the data than may have occurred if only emmetropic subjects had been used. However, interindividual variation in the changes in lens thickness per diopter of accommodation was not correlated with refractive error. Comparison of the on- and off-axis refraction measurements showed nonsystematic variation of up to 1 D. This variation may as much be the result of the on- and off-axis measurements as resulting from variations in the accommodative response to a given stimulus amplitude from one response to the next. It is this kind of variation in repeated measures of the accommodative response that may be present in other studies in which the biometry and accommodation are measured consecutively rather than simultaneously.

Previous measurements with the Hartinger coincidence refractometer in this laboratory have examined the effect of measuring refraction off-axis in the convergent eye by having a subject view distance targets at increasing off-axis positions up to 40°.[11] A variation in refraction of no more than 0.5 D was recorded for deviations of up to 22.8°. Another study showed that the refraction measured at 30° in the nasal field was 0.80 D more hyperopic in myopic children and 0.41 D more myopic in emmetropic children.[47] A subject with a normal accommodative convergence/accommodation (AC/A) ratio of 5/1[48] would converge in the measured eye no more than 20° for 7.5 D of accommodation. These values suggest that convergence would not systematically affect refraction as measured by the Hartinger with accommodation in this study. Our variations in off-axis Hartinger measured refraction are within previously reported values.[47,49]

Other instruments for measuring anterior segment biometry such as the ACMaster with PCI technology[12] and continuous ultrasonographic biometry[50] have higher precision than clinical A-scan instruments. The ACMaster is not yet available in the United States, but it may provide a method by which biometry and refraction can be measured simultaneously in the same eye.

Per-diopter biometric changes in the lens were greater in the current study compared with previous studies, in which biometry was compared with accommodative stimulus demand as opposed to accommodative response (Table 1). Using stimulus demand introduces systematic errors that increase with increasing demand as a result of the increasing lag of accommodation. In this study, the subjectively measured accommodative amplitudes were more than 2 D greater than the objectively measured amplitudes. Therefore, comparisons with subjectively measured amplitudes or accommodative stimulus demand overestimate the response amplitude and result in smaller per-diopter changes in anterior segment biometry. Simultaneous measurements of refraction in one eye and biometry in the other eye as done in the present study are likely to result in smaller dioptric errors than the errors that would result if the biometry was compared with stimulus demand rather than a measured refractive response. Interestingly, the study that reported changes most similar to those reported here actually calculated the accommodative response (as opposed to measuring it) based on measured biometry, keratometry, and phakometry.[20] The per-diopter changes reported in previous studies are more similar to the per-diopter changes found in this study when biometry is compared with the subjectively measured accommodative amplitude (Table 1).

Axial length, measured in the left eye, was linearly correlated with refractive error measured in the right eye. Average axial length of 23.86 ± 0.41 mm for emmetropic eyes is similar to previous reports of 23.31mm[51] and 23.13 mm.[52] The change in axial length per diopter of unaccommodated refractive error of 0.36 ± 0.08 mm, found in this study, is similar to previous reports of 0.35 mm/D[52] and 0.39 mm/D[53] from Stenstrom.[54]

All subjects had an anterior movement of the anterior lens surface with accommodation. However, movements of the posterior lens surface were variable. Although there was an overall posterior movement of the posterior lens surface with accommodation, 27% of subjects showed no movement or an anterior movement. Other studies of voluntary accommodation in human subjects have reported similar variability. Coleman found an overall posterior movement, but 20% of subjects showed an anterior movement. Koretz et al. found that younger subjects tended to have a posterior movement of the posterior lens surface, whereas older subjects tended to have an anterior movement.[17] In the current study, only young subjects participated, so the differences found in posterior lens movements cannot be attributed to age. Here, there was no significant relationship between per-diopter changes in biometry and refractive error, baseline lens thickness, or maximum accommodative amplitude. Interindividual variability may be the result of the measurement uncertainties related to the experimental methods presented here, which required five repeated contact measures along the visual axis for each accommodative state. In Figure 5B, one subject shows almost zero change in lens thickness for a 4-D response. Outliers such as this may be the result of several factors, including the fact that the accommodative response and biometry are measured by different individuals, measurements may not be recorded at precisely the same time, and large fluctuations in accommodation may exist in a particular subject. The precision as determined from the mean standard deviation from all eyes found in this study was 137 μm for anterior chamber depth and 109 μm for lens thickness. Similar interindividual variation was also found in a study using PCI, which is a noncontact procedure with a precision of 8 to 10 μm and resolution of 9 μm.[12]

Helmholtz, in his description of the accommodative mechanism, believed the posterior lens surface to be stationary during accommodation.[6] Based on recent studies in both humans and monkeys, this appears not to be the case.[34,55] Understanding how the lens changes in the eye and how these physical changes relate to the optical accommodative changes provides important information on the accommodative mechanism and also may lead to a better understanding of whether accommodation may be restored with artificial accommodative intraocular lenses. The small net forward movement of the lens center (defined here as half the distance from the anterior surface to the posterior surface) is largely the result of the greater anterior movement of the anterior lens surface than posterior movement of the posterior surface and is not likely to represent a real forward shift of the lens as part of the accommodative mechanism.

Previous studies in monkeys show a linear relationship between changes in refraction and biometry during Edinger-Westphal-stimulated accommodation, with all monkeys having a consistent posterior movement of the posterior lens surface.[26,34,35] The accommodative mechanism and anterior segment anatomy in Rhesus monkey eyes is similar to that of humans.[4,56] Despite differences in eye size and accommodative amplitude between humans and monkeys, the results reported here for human eyes are consistent with those reported previously in monkeys. As found in the present study, in monkeys, approximately 75% of the increase in lens thickness is the result of an anterior movement of the anterior lens surface and approximately 25% is the result of the posterior movement of the posterior lens surface.[26,34,35] Biometric changes can be measured under more controlled conditions in anesthetized monkeys with the transducer mounted in a manipulator clamped in front of the eye. On the other hand, studies in humans generally use clinical A-scan instruments in which the probe is brought in contact with the cornea and removed for each measurement. Exact alignment and placement can vary between measurements. This may account in part for the greater variability in posterior surface measurements reported during accommodation in humans. Alignment during continuous ultrasound biometry can be maintained by fixating the transducer to a cup fixed on the limbal conjunctiva with vacuum, although this instrument is not commercially available.[57]

In conclusion, changes in anterior segment biometry measured in one eye occur linearly with accommodative refractive changes in the other eye. In this study, per-diopter changes in biometry are larger than previously reported because changes have been correlated with objectively measured accommodative response rather than accommodative demand. Although there is interindividual variation, on average, the anterior surface of the lens moves anteriorly and the posterior surface of the lens moves posteriorly during a voluntary accommodative effort.

ACKNOWLEDGMENTS

The authors thank Chris Kuether for modifications to the Hartinger coincidence refractometer and Dr. Ying-Sheng Hu for statistical support.

This study was funded in part by NEI grant 1 RO1 EY014651 to AG, NEI grant P30 EY07751 to the University of Houston, College of Optometry, and NEI grant 5 T32 EY07024 to the University of Texas Health Science Center at Houston (AG and LO).

Received November 29, 2005; accepted April 3, 2006.

REFERENCES

1. Keeney AH, Hagman RE, Fratello CJ. Dictionary of Ophthalmic Optics. Boston: Butterworth-Heinemann, 1995.
2. Wilson RS. Does the lens diameter increase or decrease during accommodation? Human accommodation studies: a new technique using infrared retro-illumination video photography and pixel unit measurements. Trans Am Ophthalmol Soc 1997;95:261–7.
3. Brown N. The change in shape and internal form of the lens of the eye on accommodation. Exp Eye Res 1973;15:441–59.
4. Glasser A, Kaufman PL. The mechanism of accommodation in primates. Ophthalmology 1999;106:863–72.
5. Koretz JF, Handelman GH, Brown NP. Analysis of human crystalline lens curvature as a function of accommodative state and age. Vision Res 1984;24:1141–51.
6. Helmholtz von HH. Mechanism of accommodation. In: Southall JPC, ed. Helmholtz's Treatise on Physiological Optics. Translated from the 3rd German ed. New York: Dover Publications, 1962.
7. 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.
8. Glasser A, Wendt M, Ostrin L. Accommodative changes in lens diameter in rhesus monkeys. Invest Ophthalmol Vis Sci 2006;47: 278–86.
9. Duane A. Normal values of the accommodation at all ages. JAMA 1912;59:1010–3.
10. Hamasaki D, Ong J, Marg E. The amplitude of accommodation in presbyopia. Am J Optom Arch Am Acad Optom 1956;33:3–14.
11. Ostrin LA, Glasser A. Accommodation measurements in a prepresbyopic and presbyopic population. J Cataract Refract Surg 2004;30: 1435–44.
12. Drexler W, Baumgartner A, Findl O, Hitzenberger CK, Fercher AF. Biometric investigation of changes in the anterior eye segment during accommodation. Vision Res 1997;37:2789–800.
13. Findl O. IOL movement induced by ciliary muscle contraction. In: Guthoff R, Ludwig K, eds. Current Aspects of Human Accommodation. Heidelberg, Germany: Kaden Verlag, 2001.
14. Shum PJ, Ko LS, Ng CL, Lin SL. A biometric study of ocular changes during accommodation. Am J Ophthalmol 1993;115:76–81.
15. van der Heijde GL, de Vries-Knoppert WA. Ultrasonic measurements of accommodation in phakic and pseudophakic eyes. In: Ossoinig KC, ed. Ophthalmic Echography: Proceedings of the 10th SIDUO Congress, St. Petersburg Beach, FL, November 7–10, 1984. Dordrecht, Netherlands: Nijhoff/Junk, 1984:171–6.
16. Koretz JF, Kaufman PL, Neider MW, Goeckner PA. Accommodation and presbyopia in the human eye—aging of the anterior segment. Vision Res 1989;29:1685–92.
17. Koretz JF, Cook CA, Kaufman PL. Accommodation and presbyopia in the human eye. Changes in the anterior segment and crystalline lens with focus. Invest Ophthalmol Vis Sci 1997;38:569–78.
18. Beauchamp R, Mitchell B. Ultrasound measures of vitreous chamber depth during ocular accommodation. Am J Optom Physiol Opt 1985;62:523–32.
19. Koeppl C, Findl O, Kriechbaum K, Drexler W. Comparison of pilocarpine-induced and stimulus-driven accommodation in phakic eyes. Exp Eye Res 2005;80:795–800.
20. Kirschkamp T, Dunne M, Barry JC. Phakometric measurement of ocular surface radii of curvature, axial separations and alignment in relaxed and accommodated human eyes. Ophthal Physiol Opt 2004; 24:65–73.
21. Abramson DH, Coleman DJ, Forbes M, Franzen LA. Pilocarpine. Effect on the anterior chamber and lens thickness. Arch Ophthalmol 1972;87:615–20.
22. Findl O, Koeppl CM, Kriechbaum K, Drexler W. Pilocarpine-induced and stimulus-driven accommodation in phakic subjects and pseudophakic patients with 'accommodative' IOLs. Invest Ophthalmol Vis Sci 2004;44:E-abstract 1744.
23. Koretz JF, Bertasso AM, Neider MW, True-Gabelt BA, Kaufman PL.

Slit-lamp studies of the rhesus monkey eye: II. Changes in crystalline lens shape, thickness and position during accommodation and aging. Exp Eye Res 1987;45:317–26.
24. Patnaik B. A photographic study of accommodative mechanisms: changes in the lens nucleus during accommodation. Invest Ophthalmol 1967;6:601–11.
25. van der Heijde GL, Beers AP, Dubbelman M. Microfluctuations of steady-state accommodation measured with ultrasonography. Ophthal Physiol Opt 1996;16:216–21.
26. Vilupuru AS, Glasser A. The relationship between refractive and biometric changes during Edinger-Westphal stimulated accommodation in rhesus monkeys. Exp Eye Res 2005;80:349–60.
27. Seidemann A, Schaeffel F. An evaluation of the lag of accommodation using photorefraction. Vision Res 2003;43:419–30.
28. Subbaram MV, Bullimore MA. Visual acuity and the accuracy of the accommodative response. Ophthal Physiol Opt 2002;22:312–8.
29. Nakatsuka C, Hasebe S, Nonaka F, Ohtsuki H. Accommodative lag under habitual seeing conditions: comparison between adult myopes and emmetropes. Jpn J Ophthalmol 2003;47:291–8.
30. Rosenfield M, Cohen AS. Repeatability of clinical measurements of the amplitude of accommodation. Ophthal Physiol Opt 1996;16:247–9.
31. Atchison DA, Charman WN, Woods RL. Subjective depth-of-focus of the eye. Optom Vis Sci 1997;74:511–20.
32. Garner LF, Yap MK. Changes in ocular dimensions and refraction with accommodation. Ophthal Physiol Opt 1997;17:12–7.
33. Abramson DH, Franzen LA, Coleman DJ. Pilocarpine in the presbyope. Demonstration of an effect on the anterior chamber and lens thickness. Arch Ophthalmol 1973;89:100–2.
34. Ostrin LA, Glasser A. Comparisons between pharmacologically and Edinger-Westphal-stimulated accommodation in rhesus monkeys. Invest Ophthalmol Vis Sci 2005;46:609–17.
35. Vilupuru AS, Glasser A. Dynamic accommodative changes in rhesus monkey eyes assessed with A-scan ultrasound biometry. Optom Vis Sci 2003;80:383–94.
36. Fincham EF. The coincidence optometer. Proc Phys Soc (Lond) 1937;49:456–68. Available at: http://ej.iop.org/links/q02/zoeWyF486Luo+inE81Xc1g/prv49i5p456.pdf. Accessed May 2, 2006.
37. Troilo D, Judge SJ. Ocular development and visual deprivation myopia in the common marmoset (*Callithrix jacchus*). Vision Res 1993;33:1311–24.
38. van der Heijde GL, Weber J. Accommodation used to determine ultrasound velocity in the human lens. Optom Vis Sci 1989;66:830–3.
39. Coleman DJ, Lizzi FL, Jack RL. Ultrasonography of the Eye and Orbit. Philadelphia: Lea and Febiger, 1977.
40. Moffat BA, Atchison DA, Pope JM. Age-related changes in refractive index distribution and power of the human lens as measured by magnetic resonance micro-imaging in vitro. Vision Res 2002;42:1683–93.
41. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1:307–10.
42. Campbell FW. Correlation of accommodation between the two eyes. J Opt Soc Am 1960;50:738.
43. Koretz JF, Kaufman PL, Neider MW, Goeckner PA. Accommodation and presbyopia in the human eye. 1. Evaluation of in vivo measurement techniques. Appl Optics 1989;28:1097–102.
44. Hokoda SC, Ciuffreda KJ. Measurement of accommodative amplitude in amblyopia. Ophthal Physiol Opt 1982;2:205–12.
45. Ball EA. A study of consensual accommodation. Am J Optom Arch Am Acad Optom 1952;29:561–74.
46. Gwiazda J, Thorn F, Bauer J, Held R. Myopic children show insufficient accommodative response to blur. Invest Ophthalmol Vis Sci 1993;34:690–4.
47. Mutti DO, Sholtz RI, Friedman NE, Zadnik K. Peripheral refraction and ocular shape in children. Invest Ophthalmol Vis Sci 2000;41:1022–30.
48. Bruce AS, Atchison DA, Bhoola H. Accommodation–convergence relationships and age. Invest Ophthalmol Vis Sci 1995;36:406–13.
49. Atchison DA, Pritchard N, Schmid KL. Peripheral refraction along the horizontal and vertical visual fields in myopia. Vision Res 2006;46:1450–8.
50. Beers AP, van der Heijde GL. Age-related changes in the accommodation mechanism. Optom Vis Sci 1996;73:235–42.
51. Atchison DA, Jones CE, Schmid KL, Pritchard N, Pope JM, Strugnell WE, Riley RA. Eye shape in emmetropia and myopia. Invest Ophthalmol Vis Sci 2004;45:3380–6.
52. Wickremasinghe S, Foster PJ, Uranchimeg D, Lee PS, Devereux JG, Alsbirk PH, Machin D, Johnson GJ, Baasanhu J. Ocular biometry and refraction in Mongolian adults. Invest Ophthalmol Vis Sci 2004;45:776–83.
53. Carroll JP. Regression curves for the optical parameters of the eye. Am J Optom Physiol Opt 1981;58:314–23.
54. Stenstrom S. Investigation of the variation and the correlation of the optical elements of human eyes. Am J Optom Physiol Opt 1948;25:219–32, 286–99, 340–50, 288–97, 438–49, 496–504.
55. Koeppl C, Findl O, Kriechbaum K, Drexler W. Comparison of pilocarpine-induced and stimulus-driven accommodation in phakic eyes. Exp Eye Res 2005;80:795–800.
56. Koretz JF, Neider MW, Kaufman PL, Bertasso AM, DeRousseau CJ, Bito LZ. Slit-lamp studies of the rhesus monkey eye. I. Survey of the anterior segment. Exp Eye Res 1987;44:307–18.
57. Beers AP, Van der Heijde GL. Presbyopia and velocity of sound in the lens. Optom Vis Sci 1994;71:250–3.

Adrian Glasser
University of Houston College of Optometry
505 J Davis Armistead Building
Houston, TX 77004
e-mail: aglasser@uh.edu