

---

# Accommodation and Presbyopia in the Human Eye

## Changes in the Anterior Segment and Crystalline Lens With Focus

Jane F. Koretz,\* Christopher A. Cook,† and Paul L. Kaufman‡

**Purpose.** To characterize changes in the sagittal dimensions of the human crystalline lens and anterior segment as a function of accommodation, to determine the potential age dependence of these changes, and to evaluate these changes in relation to the development of presbyopia.

**Methods.** Scheimpflug slit-lamp photography, as well as a variety of standard ophthalmologic methods, was used to collect information about lens and anterior segment sagittal dimensions in a population of 82 adults with refractive error  $\leq |2.0|$  diopters and at least 0.25 diopter of accommodation for subjects 18 to 70 years of age. Data were analyzed statistically for dependence on accommodation, age, and age dependence of accommodative rate.

**Results.** The rate of change per diopter of accommodation for each measured variable within the lens is independent of age for the entire adult age range. With increasing accommodation, the lens becomes thicker and the anterior chamber shallower along the polar axis. This increase in sagittal lens thickness is entirely because of an increase in the thickness of the lens nucleus. Because the anterior and posterior halves of the nucleus increase in thickness at approximately the same rate with accommodation, the increase in lens thickness results from equal changes in the lengths of the anterior and posterior portions.

**Conclusions.** Because changes along the sagittal axis of the anterior segment with accommodation are independent of age, any explanation of presbyopia that relies on simple changes in the rates of lens thickening and anterior chamber shallowing with age does not hold. In light of other age-related changes in the anterior segment and lens (e.g., increased sharpness of lens curvature, increased lens sagittal thickness, decreased anterior chamber depth), it appears that compensatory mechanisms to preserve far vision with age also preserve the rate of change per diopter of sagittal spacings. *Invest Ophthalmol Vis Sci.* 1997;38:569–578.

Accommodation, the process by which the eye focuses on near objects, occurs in humans through the carefully controlled deformation of the crystalline lens. In a small ( $N = 4$ ) data set, Brown<sup>1</sup> and later Koretz et al,<sup>2</sup> in a reanalysis of these data, showed that as focus increases, lens thickness and sharpness of the anterior and posterior lens curvatures also increase, primarily because of an increase in sagittal thickness of the lens nucleus; the center of lens mass is moved

anteriorly; and the anterior chamber becomes shallower as the lens anterior surface moves forward. Whether the posterior surface of the lens changes location during this process has not been determined definitively, although evidence of overall lens movement in either direction has been observed. Ciliary muscle contraction reduces the forces acting on the lens because of the geometric relation between the lens, the zonular apparatus, and the ciliary muscle. This results in elastic recovery or “rounding up” of the lens. Concomitantly, when the eye is focused on infinity, the ciliary muscle is relaxed and the lens is under maximal applied stress.

With increasing age, the lens becomes larger and its center of mass is moved anteriorly, because the distance from the cornea to the posterior lens surface along the pole largely remains unchanged.<sup>3</sup> As a result, the anterior chamber becomes shallower by the

---

From the Center for Biophysics and Departments of \*Biology and †Physics, Rensselaer Polytechnic Institute, Troy, New York; and the ‡Department of Ophthalmology, University of Wisconsin Clinical Science Center, Madison, Wisconsin.

Supported by National Institutes of Health grant EY02195.

Submitted for publication August 14, 1996; revised October 11, 1996; accepted October 14, 1996.

Proprietary interest category: N.

Reprint requests: Jane F. Koretz, Department of Biology SC, Rensselaer Polytechnic Institute, Troy, NY 12180-3590.

same amount as lens thickness increases. This increase entirely is because of an increase in anterior and posterior cortical widths, with the sagittal thickness of the nucleus unchanged. Because anterior segment length and posterior cortical growth are fixed, this change indicates that lens aging is accompanied by an anterior translation of the lens nucleus equal to the thickening of the posterior cortex.

Other changes occur in the lens and anterior segment with increasing age. Brown<sup>4</sup> showed that central lens curvature on both the anterior and posterior surfaces becomes sharper in the unaccommodated eye with increasing age. Farnsworth and Shyne<sup>5</sup> showed that the diameter of the anterior zonular attachments to the lens capsule essentially remains unchanged with age; because the anterior lens surface is moved in relation to both the cornea and the posterior lens surface by overall lens growth, the three-dimensional relation between the lens, zonules, and ciliary muscle gradually is being altered. Tamm et al<sup>6</sup> observed that the location of the anterior part of the ciliary muscle is moved anteriorly and inwardly with age. Whether this is the cause of increased anterior lens sharpness is unclear, but the constant sagittal nuclear thickness contravenes lens relaxation being associated with the shift in ciliary muscle position; rather, it is likely that increased lens thickness, coupled with a constant anterior segment length, pulls the ciliary muscle into its new position.

With increasing age, there is a reduction in the total accommodative range, with the nearest point of focus receding gradually toward the far point. This loss of accommodative amplitude is correlated strongly with several of the above-mentioned changes in the anterior segment,<sup>7,8</sup> most notably lens growth and anterior chamber shallowing. Koretz and Handelman<sup>9</sup> have suggested that presbyopia is therefore a result of the gradually altered anterior segment geometry, with increased lens thickness and altered anterior lens location, combined with the unchanged position of the zonular attachments to the lens relative to its center of symmetry, resulting in a gradual loss of mechanical effectiveness.

To investigate aging of the accommodative mechanism in more depth and to determine what changes may be associated directly with the gradual loss of accommodative amplitude, the accommodative process has been studied through analysis of Scheimpflug slit-lamp photographs of 100 adults with emmetropia distributed evenly in age with a range of 18 to 70 years. The current study of the aging of accommodation is directed to the analysis of sagittal dimensional changes in the anterior segment, and especially the lens, as a function of accommodation, and characterization of the aging of the rate at which these changes occur.

The 82 data sets remaining after elimination of subjects without any accommodative amplitude provide information of sufficient statistical strength to characterize these processes.

## MATERIALS AND METHODS

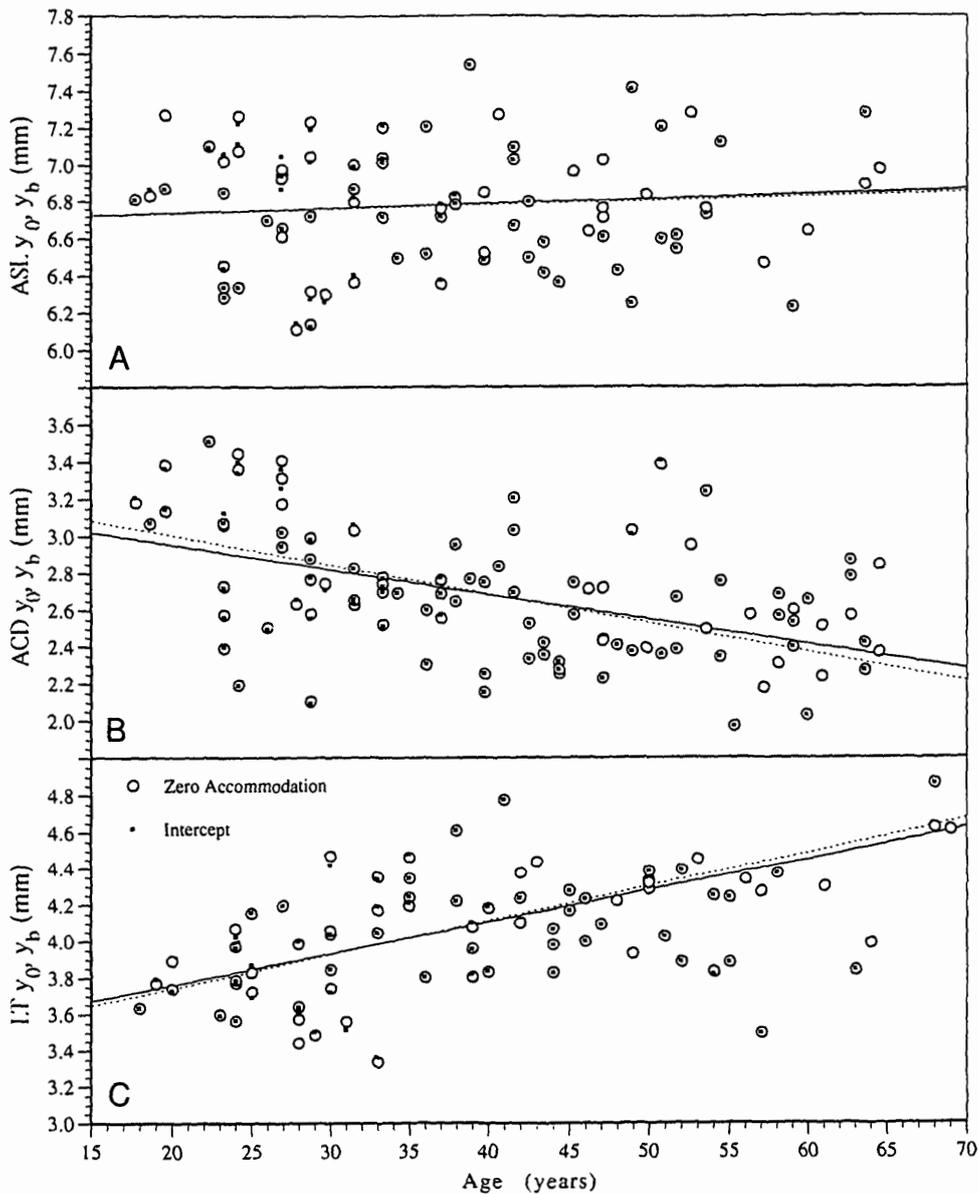
### Data Collection

The sample population and the techniques used to collect and analyze accommodation data have been described previously in detail.<sup>3,7,8,10</sup> In summary, 100 male and female human volunteers distributed evenly for the 18- to 70-year age range were studied according to the Declaration of Helsinki and in an Independent Review Board-approved experimental protocol. After discussing the protocol and providing their informed consent in writing, these adult subjects were screened using exclusion criteria, which required blood pressure below 140/90, clear crystalline lenses, refractive error  $\leq |2.0|$  diopters (D), and astigmatism confined to the 0 or 90° orientation and  $\leq 1.0$  D. Biometric data were collected by standard techniques (e.g., keratometry, pachymetry) before dilation of the right eye using one or two drops of 10% phenylephrine for Scheimpflug slit-lamp photography.

The Scheimpflug slit-lamp setup consists of the camera and an accommodation target as described previously.<sup>7,8</sup> Accommodative amplitude attained by the left eye in focusing on the target was controlled using trial frames and selected lenses placed in front of this eye at 2.0-D intervals ranging from infinity to the closest obtainable focal point; when the subject-indicated focus with the left eye had been achieved, a slit-lamp photograph of the dilated right eye was taken. A similar accommodation setup, but with a Hartinger refractometer replacing the slit-lamp camera, was used to determine the refractive error of the right eye when the left eye was focused on an identical target; the dilated right eye's accommodative amplitude matches that of the undilated left eye.<sup>8</sup> For older subjects where total accommodative amplitude was  $< 2.0$  D, and for subjects where the closest focal point was not a multiple of 2.0 D, lesser accommodative challenges were presented to obtain data about the right eye at the point of closest focus. After the photographic series was completed, data on pupil diameter, intraocular pressure, and axial ocular dimensions were obtained, the latter using A-scan ultrasonography.

### Data Analysis

The slit-lamp photographic negatives were digitized using a video camera and a Data Translation frame grabber board interfaced with a Macintosh Ilcx and stored



**FIGURE 1.** Intercepts for selected variables obtained by extrapolation of accommodation-dependent data back to 0 diopter ( $Y_b$ ), compared with data collected on unaccommodated eyes ( $Y_0$ ). For these and other measured variables, the sample populations are the same at the 95% confidence level using the paired *t*-test; **(A)** anterior segment length (ASL); **(B)** anterior chamber depth (ACD); **(C)** lens thickness (LT). Point symbols and dotted lines represent the extrapolated values and their weighted least-squares fit, whereas open symbols and solid lines represent measured values at 0 diopter and the weighted least-squares fit.

on an Optical Access International 1-Gb optical disk (Panasonic, Matsushita Electric Industrial, Osaka, Japan). They then were calibrated, normalized, and corrected for slit-lamp and digitizing camera distortions and other distortions as described previously.<sup>10</sup> For the current study, the following data were collected from each image of each slit-lamp set for each subject: accommodative amplitude (measured as refractive error and converted to change in dioptric power relative to the unaccommodated state) of the right eye, anterior

chamber depth, anterior cortical thickness, anterior nuclear thickness including the central sulcus, posterior nuclear thickness, and posterior cortical thickness. Five other variables, the sum of two or more of the listed measurements, also were considered: anterior lens thickness (anterior lens surface to center of nucleus, including the central sulcus), posterior lens thickness (posterior edge of central sulcus to posterior lens surface), total nuclear thickness, total lens thickness, and anterior segment length. Subjects unable to accommo-

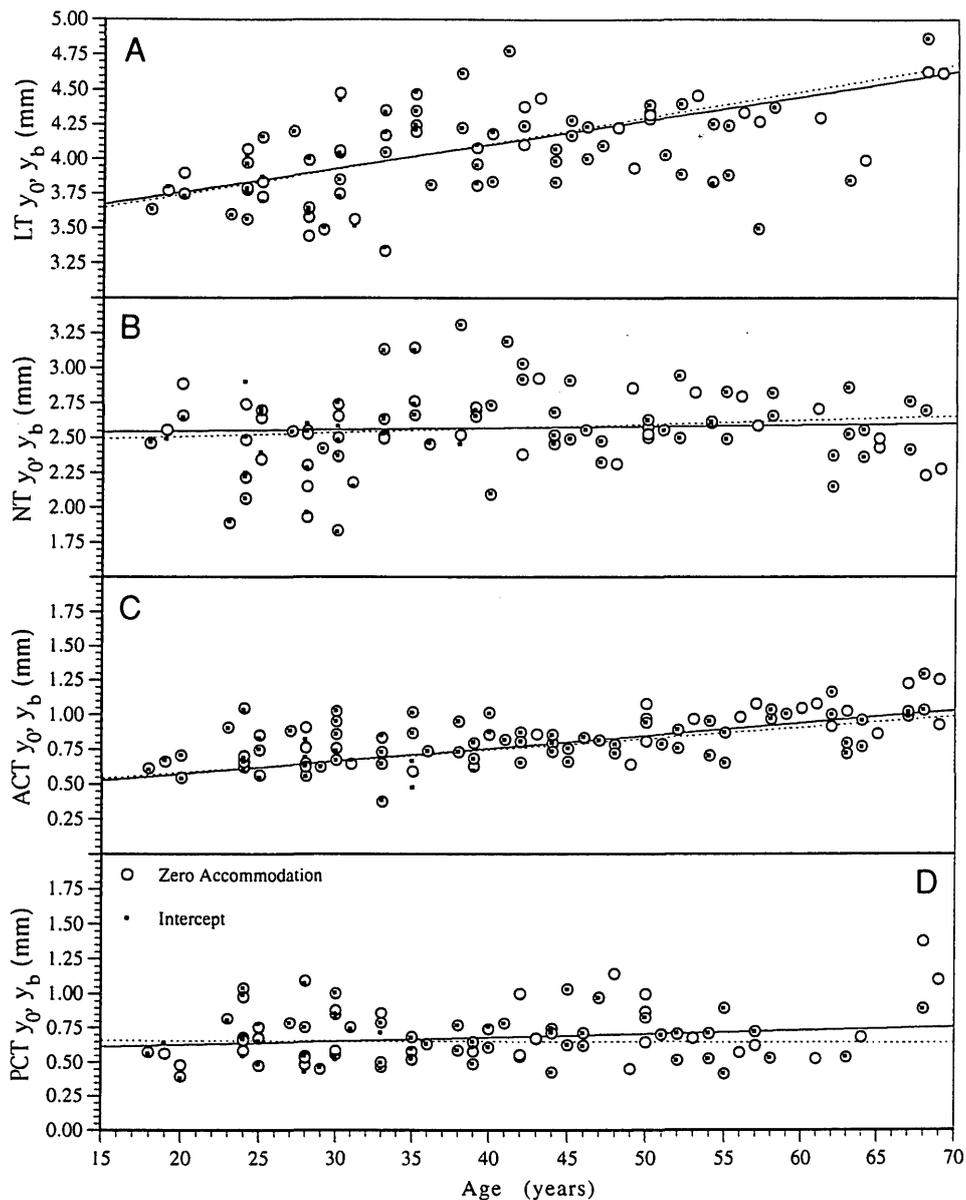


FIGURE 2. As in Figure 1, with the lens and its regions considered separately. (A) Lens thickness (LT); (B) nuclear thickness (NT); (C) anterior cortical thickness (ACT); and (D) posterior cortical thickness (PCT).

date (i.e., an accommodative range of  $<0.25$  D) were eliminated, leaving 82 subjects, 42 between the ages of 18 and 40 years, and 40 between the ages of 41 and 70 years. This demarcation divides the subjects roughly equally into two groups exhibiting accommodative amplitudes  $\geq 2$ D and  $\leq 2$ D respectively.

For each subject, the slope and the intercept of the best-fitting line for each variable as a function of accommodative amplitude were determined by the weighted least-squares method, using an instrumental error of 0.015 mm. These data allow an analysis of the possible age dependence of the slope and intercept of each variable, with each datum weighted by its stan-

dard deviation. For example, the slope for each subject's lens thickness as a function of accommodative amplitude was determined, then the slopes for all subjects tested collectively to determine whether the change in lens thickness per diopter accommodation changed with age. In addition, the intercept of the best-weighted least-square line fitting the accommodation dependence of each measured variable was compared to the 0-D measurement of that variable. If the accommodation dependence of each variable truly is linear, then the best-fitting line for each, extrapolated back to 0 D, will define values for the intercepts that, when plotted as a function of subject age, should be

**TABLE 1.** Rate of Change During Accommodation for Subjects 18 to 40 Years of Age (n = 42)

<i>Variable</i>	<i>Mean</i>	<i>Standard Deviation</i>	<i>Skew</i>	<i>Kurtosis</i>
Anterior chamber depth	-0.037	0.026	0.01	2.37
Anterior cortex	0.002	0.013	4.56	26.35
Anterior lens to sulcus	0.025	0.019	0.85	3.55
Anterior nucleus plus sulcus	0.023	0.026	2.18	7.32
Posterior nucleus	0.018	0.023	2.43	11.25
Posterior cortex	0.000	0.031	-1.39	10.30
Posterior lens to sulcus	0.018	0.021	-1.33	4.50
Total nuclear thickness	0.041	0.029	1.58	6.30
Total lens thickness	0.043	0.027	-0.59	3.46
Anterior segment length	0.003	0.035	-0.06	2.46

Values are in millimeter per diopter. The means derived by averaging the slopes of the accommodation-dependent relationships are internally consistent; that is, the sum of the means of the lens components equals the change in anterior chamber depth and anterior segment length to 0.003 mm/diopter. The large standard deviations result from an assumption of a normal distribution around the mean and from the scatter in these data sets, arising from the small number of measured points defining the slope of these relationships for each human subject. Skew is a statistical function evaluating the degree of asymmetry around the mean; a perfect normal distribution would have a skew value of 0.0. Kurtosis is a statistical function related to the sharpness of a normal distribution, which would show a value of 3.0. Larger values indicate narrower distributions. See also references. 12 and 13.

identical statistically to the relations determined previously for the nonaccommodated eye.<sup>3</sup> For those variables that were independent of age ( $P > 0.05$ ), the weighted mean, standard deviation, skew, and kurtosis of the distributions were calculated assuming a normal distribution for each sample; these four parameters can be considered the first-, second-, third-, and fourth-order moments of the data sets.<sup>11,12</sup>

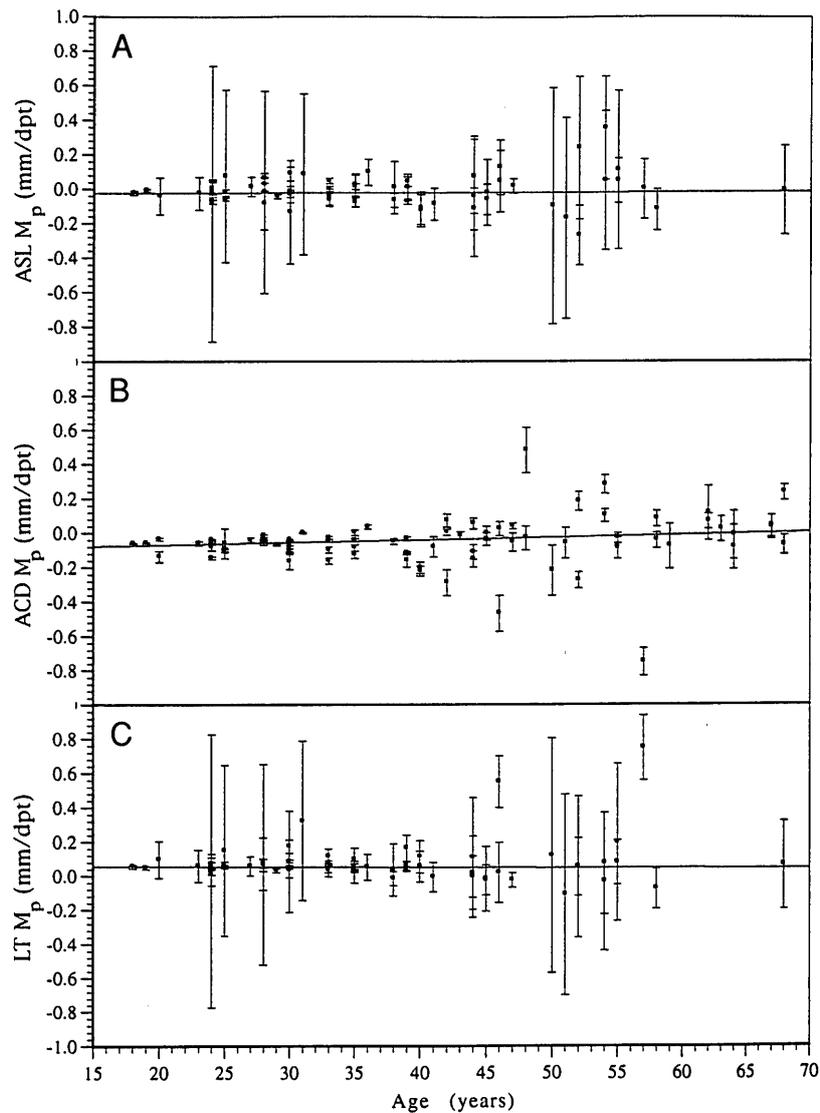
**RESULTS**

Figures 1 and 2 show the intercepts of accommodation-dependent relations extrapolated back to 0 D plotted as a function of age for some of the measured variables (points), with the equivalent data from the nonaccommodated eyes plotted for comparison (open symbols). Figure 1 illustrates the age dependence and accommodation-dependent linearity of spacings related to the anterior segment (anterior segment length, anterior chamber depth, and lens thickness). Figure 2 illustrates the age- and accommodation-dependent changes in lens regional dimensions (nuclear thickness, anterior cortical thickness, and posterior cortical thickness). For every variable, whether illustrated or not, a paired *t*-test indicates statistical identity of the accommodation intercept value and the 0-D value at the 95% confidence level, ensuring both consistency of the methods and linearity of the relations as a function of accommodation.

The dynamics of the accommodative process appear to be qualitatively the same for all subject ages, albeit with considerable quantitative interindividual

variation, especially in the older, presbyopic lenses. As accommodation increases, the lens becomes thicker along the sagittal axis, due almost entirely to an increase in nuclear sagittal thickness. Cortical lens thickness along this axis shows little or no change. Thus, the central clear zone, anterior nuclear boundary, and anterior lens surface are translated anteriorly by these changes in nuclear shape, with the translation of the latter two relative to the posterior lens surface equal to the total change in nuclear thickness. As a result of lens thickening, the anterior chamber becomes shallower.

Quantitative analysis of these processes, using the slopes of the linear, accommodation-dependent relations for all subjects aged 40 years or younger (N = 42), provides information about both the specific relations being altered during accommodation and their age dependence. For this population sample, all of the measured variables are independent of age ( $P > 0.05$ ); that is, the change in thickness or distance of each per diopter of accommodation is constant for the age range of 18 to 40 years, although there can be considerable interindividual variation. The data sets then were reanalyzed using histogram analysis (Table 1) to determine the weighted average value, standard deviation, skew, and kurtosis. The very large kurtosis values for some of these variables indicate that those data distributions are much narrower than would be expected for a normal distribution around the mean, whereas the nonzero skew values indicate an asymmetric distribution of measured values around the mean. Because the standard deviation is calculated



**FIGURE 3.** The rate of change per diopter ( $M_p$ ) as a function of subject age of the thickness of (A) anterior segment length (ASL); (B) anterior chamber depth (ACD); and (C) lens thickness (LT). For subjects 40 years of age or younger, the variation in individual measurements and the error associated with each measurement generally are smaller than those from older subjects. Despite the larger variations in the older subjects, however, these rates are age independent ( $P > 0.05$ ) for the entire age range.

on the assumption of a normal distribution, it is an overestimate of the error associated with each mean value when the kurtosis is larger than 3.0, in that the histograms are pointed and concave, whereas the range defined by the standard deviation on either side of the mean must incorporate approximately 67% of all the data points.

Subjects younger than or equal to 40 years of age generally exhibit an accommodation range  $\geq 4$  D, but older subjects show ranges  $\leq 2$  D; in the latter case, the limited data on changes per diopter of accommodation, combined with an instrumental error in measurement accuracy of  $\sim 0.015$  mm, results in variables

with larger associated standard deviations than generally are seen in the younger subjects. It nevertheless seemed important to determine whether, when these data ( $N = 40$ ) on presbyopes were added to the data set for younger subjects, there was a change in the characteristics of each variable per diopter accommodation. Figures 3 and 4 show the rate of change per diopter of the variables of Figures 1 and 2, plotted with their standard deviations as a function of age, for the entire ( $N = 82$ ) population. For each plot, the variation generally increases past age 40, but the overall relation remains age independent; this observation holds true for all the measured or composite variables

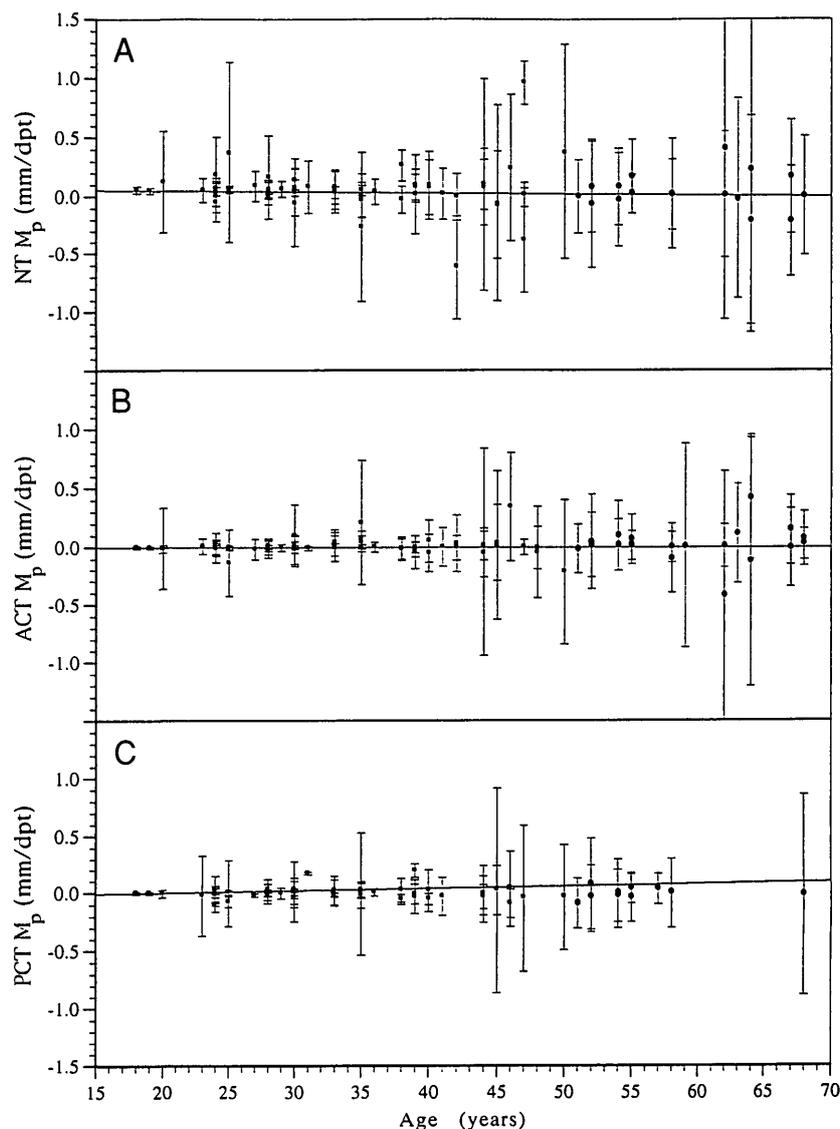


FIGURE 4. As in Figure 3, with lens regions considered separately. (A) Nuclear thickness (NT); (B) anterior cortical thickness (ACT); and (C) posterior cortical thickness (PCT).

and is confirmed by statistical analysis of the age dependence, where  $P > 0.05$ . Histogram analysis (Table 2) of the complete data set shows little or no difference in the values of the weighted means; the standard deviations, however, are increased greatly in magnitude. Thus, the changes in spacing per diopter in the lens during accommodation essentially are the same for the entire adult age range where accommodation is possible.

### DISCUSSION

The accommodative process in the human eye primarily relies on the change in shape and thickness of the crystalline lens and a decrease in the distance between the cornea and the anterior lens surface. As noted

previously for a small sample<sup>1,2</sup> and herein for a large one, the change in lens thickness entirely is because of an increase in the thickness of the lens nucleus along the polar axis; the distribution between anterior and posterior nuclear thickness increase roughly is divided evenly between the two, and cortical thickness essentially is unchanged for the entire range.

The most surprising aspect of this process is that the rate of thickness change of each relevant region is not age dependent. Although the distribution of internal lens changes is somewhat variable between regions in different persons, the averaged process overall is the same regardless of the total accommodative amplitude. These results strongly contrast with preliminary analyses of lens curvature changes on aging and accommodation. Brown<sup>4</sup> showed that for

**TABLE 2.** Rate of Change During Accommodation For Subjects 18 to 70 Years of Age ( $n = 82$ )

<i>Variable</i>	<i>Mean</i>	<i>Standard Deviation</i>	<i>Skew</i>	<i>Kurtosis</i>
Anterior chamber depth	-0.038	0.139	2.82	10.43
Anterior cortex	0.002	0.034	3.43	23.41
Anterior lens to sulcus	0.025	0.088	-0.46	9.43
Anterior nucleus plus sulcus	0.023	0.087	-1.10	7.81
Posterior nucleus	0.018	0.069	-1.34	7.35
Posterior cortex	0.000	0.076	-2.19	10.83
Posterior lens to sulcus	0.017	0.108	-2.53	10.65
Total nuclear thickness	0.041	0.120	-2.78	16.41
Total lens thickness	0.043	0.145	-3.68	21.18
Anterior segment length	0.003	0.174	1.48	10.53

Values are in millimeter per diopter.

As in Table 1, but for the complete set of persons demonstrating at least 0.25 diopter of accommodation. Note that the weighted means essentially are unchanged in value, whereas the standard deviations are sizably increased. This is caused in part by the decreased reliability of the data from older persons and in part by the sharpness of the distribution, as indicated by the kurtosis value.

the aging, nonaccommodated lens, both lens surfaces become more sharply curved, with the anterior surface changing more rapidly than the posterior with age. Because, despite this increased sharpness of lens curvature, it is near vision and not far vision that is lost with age (Brown's "lens paradox"), it has been suggested that the refractive index gradient of the lens must somehow change with increasing age to compensate.<sup>9,13</sup> For an accommodated lens, as studied in small preliminary data sets, this same process occurs.<sup>1</sup> Internal lens curvatures, delineated by the nuclear margin and the zones of discontinuity, become more sharply curved at the same rate as the surface.<sup>2,14</sup> Although this general relation is maintained with lens aging, the rate of change is altered with age.

By integrating these observations and recalling that the spacings between the zones of discontinuity within the cortex along the polar axis remain constant for a given lens during accommodation,<sup>2,15</sup> the specific events of the accommodative process can be described. As the stresses exerted by the ciliary muscle are reduced by muscle contraction, the nucleus becomes thicker and more sharply curved, moving the anterior lens surface closer to the cornea. At the same time, the external lens surfaces and the internal boundaries also become more sharply curved, with changes in radii of curvature that can be defined specifically with age. The spacings between these internal curves within each cortical region remain constant along the polar axis, but the anterior and posterior cortex become separated more distantly as the nucleus thickens. For younger eyes, the posterior lens surface may tend to move posteriorly a short distance as well, so that total anterior segment length may increase slightly.

For the presbyopic eye, the general accommodative mechanism appears to be the same as for the prepresbyopic eye, but the range over which this mechanism operates is vanishingly small. The minuscule changes in lens thickness and related variables per diopter nevertheless agree with values for changes in the younger eyes obtained with more data per subject. The one major difference between the older and younger eyes, aside from accommodative amplitude, is the direction of movement of the posterior lens surface relative to the cornea. A majority of the younger group exhibits a slight movement of this surface posteriorly during accommodation, whereas a majority of the older group exhibits an anterior movement of this surface accompanied by greater anterior chamber shallowing. Although the magnitude of this translation is not statistically significant for either group or as a whole, it is possible that in the older subjects, an anterior translation of the lens may act secondarily to contribute a small amount (perhaps 0.25 D) of extra accommodative amplitude.

The uniformity in length changes per diopter in the focusing process for the age range where accommodation is possible makes an explanation of Brown's lens paradox even more difficult, because a gradually altered, and presumably shallower, refractive index gradient with age superficially would seem to require a greater degree of lens deformation per unit accommodation than appears to occur. The solution to this problem may be twofold, dependent on aging changes in lens shape as well as changes in the refractive indexes of the lens material. The curvatures of the lens boundaries increase in sharpness with both age and accommodation.

These boundaries, which can be approximated well by parabolic surfaces, will become more sharply curved peripherally as well as centrally; the rate of peripheral sharpening will increase with increasing central sharpness of curvature. As a result, the magnitude of peripheral lens deformation will increase with increasing accommodative amplitude and, more significantly, with age. Koretz and coworkers<sup>16,17</sup> have illustrated this phenomenon for a small data set, showing that a given peripheral point is translated both anteriorly and inwardly, and that the magnitude of the distance traveled is a function of both initial location and subject age.

The underlying cause of a change in lens refractive index gradient with age remains unclear. One possibility<sup>19</sup> is that each zone of discontinuity exhibits a refractive index slightly less than its adjacent neighbors, due both to a reduction in the concentration of soluble protein and to a concomitant increase in the size of soluble and insoluble particles. Such regions, interleaved with regions of higher refractive index, would reduce the overall refractive power of the lens at all levels of accommodation. Furthermore, the increase in both their number<sup>15</sup> and their density<sup>3</sup> with increasing age could correlate well with the hypothesized gradual decrease in refractive power necessary to balance the increased sharpness of curvature associated with the lens paradox, particularly in reference to the current results. Munger et al<sup>18</sup> provide experimental evidence consistent with this hypothesis. A shallowing of the lenticular refractive index gradient<sup>19</sup> based on an age-related reduction in nuclear refractive index, due to changes in the state of the nuclear proteins and age-related increases in the amount of free water as determined by Raman microspectroscopy,<sup>20</sup> also has been suggested. Either possibility obviates the necessity of hypothesizing significant changes in the steepness of the gradient of the human crystalline lens margins with age, although this may occur as well. In the final analysis, however, the age-dependent changes in lens shape and lens refractive index gradient appear to compensate each other sufficiently well that the accommodative changes in lens and anterior segment spacings along the sagittal axis per diopter are unaltered with increasing age.

In conclusion, lens thickness, nuclear thickness, and anterior chamber depth change linearly as a function of increased accommodative amplitude, and the rate at which these changes occur is unaltered with increasing subject age and concomitant decrease in accommodative range. The constancy of these rates of change independent of age implies that both the overall lens refractive contribution and the rate of

change with accommodation of refractive contribution are preserved. It also suggests that other lens and anterior segment changes, which are age dependent, develop in a compensatory manner to preserve far vision and the general form of the accommodative process.

### Key Words

accommodation, anterior chamber, anterior segment, lens, presbyopia

### Acknowledgments

The authors thank Arnold Pfahnl and John Hyun for their technical contributions.

### References

1. Brown NP. The change in shape and internal form of the lens of the eye on accommodation. *Exp Eye Res.* 1974;15:441–459.
2. Koretz JF, Handelman GH, Brown NP. Analysis of human crystalline lens curvature as a function of accommodative state and age. *Vision Res.* 1984;24:1141–1151.
3. Cook CA, Koretz JF, Pfahnl A, Hyun J, Kaufman PL. Aging of the human crystalline lens and anterior segment. *Vision Res.* 1994;34:2945–2954.
4. Brown NP. The change in lens curvature with age. *Exp Eye Res.* 1974;19:175–183.
5. Farnsworth PN, Shyne SE. Anterior zonular shifts with age. *Exp Eye Res.* 1979;28:291–297.
6. Tamm S, Tamm E, Rohen JW. Age-related changes of the human ciliary muscle: A quantitative morphometric study. *Mech Ageing Dev.* 1992;62:209–221.
7. Koretz JF, Kaufman PL, Neider MW, Goeckner PA. Accommodation and presbyopia in the human eye. I: Evaluation of in vivo measurement techniques. *Applied Optics.* 1989;28:1097–1102.
8. Koretz JF, Kaufman PL, Neider MW, Goeckner PA. Accommodation and presbyopia in the human eye—aging of the anterior segment. *Vision Res.* 1989;29:1685–1692.
9. Koretz JF, Handelman GH. How the human eye focuses. *Sci Am.* 1988;259:92–99.
10. Cook CA, Koretz JF. Acquisition of the curves of the human crystalline lens from slit-lamp images: An application of the Hough transform. *Applied Optics.* 1991;30:2088–2099.
11. Bevington PR. *Data Reduction and Error Analysis for the Physical Sciences.* New York: McGraw-Hill; 1969.
12. Press WH, Flannery BP, Teukolsky SA, Vetterling WT. *Numerical Recipes: The Art of Scientific Computing.* New York: Cambridge University Press; 1989.
13. Koretz JF, Handelman GH. The “lens paradox” and image formation in accommodating human eyes. In *The Lens: Transparency and Cataract, Topics in Aging Research in Europe 1986*;6:57–64.
14. Cook CA, Koretz JF. Age-dependent changes in internal lens dynamics during accommodation. *Proc IX ICER 1990*;6:274.

15. Koretz JF, Cook CA, Kuszak JR, Kaufman PL. The zones of discontinuity in the human lens: Development and distribution with age. *Vision Res.* 1994; 34:2955–2964.
16. Koretz JF, Handelman GH. Internal crystalline lens dynamics during accommodation: Age-related changes. *Atti Fondazione Ronchi.* 1985;40:409–416.
17. Koretz JF, Cook CA, Handelman GH. Preliminary modeling of human crystalline lens deformation during accommodation as a function of age. *Optical Society of America Tech. Digest* 1996;98–101.
18. Munger R, Campbell MCW, Kroger RHH, Burns CM. Refractive index profiles of crystalline lenses with a visible region of opacity. *ARVO Abstracts. Invest Ophthalmol Vis Sci.* 1992;33:1169.
19. Cook CA, Koretz JF. Modeling the optical properties of the aging human crystalline lens from computer processed Scheimpflug images in relation to the lens paradox. *Optical Society of America Tech. Digest* 1995;138–142.
20. Siebinga I, Vrensen GFJM, De Mul FFM, Greve J. Age-related changes in local water and protein content of human eye lenses as measured by Raman microspectroscopy. *Exp Eye Res.* 1991;53:233–239.