

# Power Vector Analysis of Refractive, Corneal, and Internal Astigmatism in an Elderly Chinese Population: The Shihpai Eye Study

Yu-Chi Liu,<sup>1,2,3</sup> Pesus Chou,<sup>4</sup> Robert Wojciechowski,<sup>5</sup> Pei-Yu Lin,<sup>1,6</sup>  
Catherine Jui-Ling Liu,<sup>1,6</sup> Shib-Jen Chen,<sup>1,6</sup> Jorn-Hon Liu,<sup>7</sup> Wen-Ming Hsu,<sup>3,8</sup>  
and Ching-Yu Cheng<sup>1,2,9,10</sup>

**PURPOSE.** To investigate age-related trends in refractive, corneal, and internal astigmatism and to assess the association between internal astigmatism and lens opacity in an elderly Chinese population.

**METHODS.** A population-based study was conducted among 1360 inhabitants aged 65 years and older in Taipei, Taiwan. Participants underwent measurements of refraction, corneal dioptric power, and slit lamp biomicroscopy with lens grading. A total of 2084 eyes were included in power vector analyses of Cartesian astigmatism ( $J_0$ ) and oblique astigmatism ( $J_{45}$ ) components of refractive, corneal, and internal astigmatism.

**RESULTS.** The crude prevalence of refractive astigmatism (defined as  $\geq 0.75$  diopters) was 73.0% based on the right eyes and 76.4% based on the left eyes. The vector values in both refractive  $J_0$  and corneal  $J_0$  tended to be more negative with increasing age ( $P < 0.001$ ), indicating the trend toward against-the-rule (ATR) astigmatism. Corneal  $J_0$  alone accounted for 54% of the variability in refractive  $J_0$ . Refractive  $J_{45}$  increased with age in the right eyes ( $P < 0.001$ ) and decreased slightly with age in the left eyes ( $P = 0.012$ ). Cortical opacity was associated with internal  $J_0$  ( $P = 0.025$ ), but the association was weak.

**CONCLUSIONS.** Astigmatism affects approximately three quarters of the Chinese population aged 65 years and older in Taiwan. With increasing age, the prevalence of astigmatism increases,

and refractive and corneal astigmatism shift toward ATR. Continuous corneal changes appear to be responsible for the age trend in refractive astigmatism. The severity of lens opacity plays only a minor role in the change of internal astigmatism. (*Invest Ophthalmol Vis Sci.* 2011;52:9651-9657) DOI:10.1167/iovs.11-7641

Astigmatism is a common type of refractive error and may greatly influence uncorrected visual acuity. The prevalence of astigmatism increases with age,<sup>1-6</sup> and there are aging effects on both corneal and refractive astigmatism.<sup>7-9</sup> With increasing longevity, there is a rising percentage of elderly population worldwide. However, most population-based studies on astigmatism have been conducted among young and middle-aged adults or included only a small proportion of elderly participants.<sup>1-4,6-8</sup> Information on astigmatism in the elderly, especially of its refractive, corneal, and internal astigmatic components, is limited. Some literature has suggested that changes in the blur component of best-corrected visual acuity in the elderly could be attributed to changes in ocular astigmatism.<sup>10</sup> Therefore, astigmatism in the elderly becomes an important clinical and public health issue.

With advancing age, the axes of refractive and corneal astigmatism shift from with-the-rule (WTR) toward against-the-rule (ATR).<sup>7,8,11,12</sup> Although some authors have suggested that the refractive ATR trend is related to changes in the cornea,<sup>7,13,14</sup> the mechanism and process of the shift in the axis have not been clarified even after analyzing data separately in terms of magnitude and axis of astigmatism. Knowing age-related trends of astigmatism in the elderly is helpful in predicting long-term outcomes of refractive surgeries and refractive changes after cataract surgery.

The effects of different morphologic types of age-related lens opacity on astigmatism are not clear. Early experimental studies found no evidence that age-related lens opacity causes astigmatic changes,<sup>15,16</sup> but more recent studies have suggested that cortical opacity can induce astigmatism,<sup>17,18</sup> whereas others have reported that nuclear sclerotic cataract<sup>3,19</sup> can cause more astigmatic changes. However, these studies used refractive astigmatism measurement to evaluate the relationship between lens opacity and astigmatism, which cannot eliminate the aging effects of corneal components. Therefore, internal astigmatism may provide a more adequate exploration. It is obtained as the difference between refractive and corneal astigmatism and is the result of the internal optics of the eye, including the crystalline lens.

When the axes of refractive and corneal astigmatism are parallel, internal astigmatism can be derived from directly subtracting corneal astigmatism from refractive astigmatism. How-

From the <sup>1</sup>Department of Ophthalmology, Taipei Veterans General Hospital, Taipei, Taiwan; <sup>2</sup>Singapore Eye Research Institute, Singapore; <sup>3</sup>Department of Ophthalmology, School of Medicine, Taipei Medical University, Taipei, Taiwan; <sup>4</sup>Community Medicine Research Center and Institute of Public Health and <sup>6</sup>Department of Ophthalmology, National Yang-Ming University, Taipei, Taiwan; <sup>5</sup>Department of Epidemiology, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland; <sup>7</sup>Department of Ophthalmology, Cheng Hsin General Hospital, Taipei, Taiwan; <sup>8</sup>Department of Ophthalmology, Shuang Ho Hospital-Taipei Medical University, Taipei, Taiwan; <sup>9</sup>Saw Swee Hock School of Public Health, and Department of Ophthalmology, Yong Loo Lin School of Medicine, National University of Singapore, Singapore; and <sup>10</sup>Centre for Quantitative Medicine, Office of Clinical Sciences, Duke-NUS Graduate Medical School, Singapore.

Supported by Taipei Veterans General Hospital Grants VGH 89-404 and VGH 90-445-1.

Submitted for publication March 27, 2011; revised September 14 and October 26, 2011; accepted November 2, 2011.

Disclosure: Y.-C. Liu, None; P. Chou, None; R. Wojciechowski, None; P.-Y. Lin, None; C.J.-L. Liu, None; S.-J. Chen, None; J.-H. Liu, None; W.-M. Hsu, None; C.-Y. Cheng, None

Corresponding author: Ching-Yu Cheng, Department of Ophthalmology, National University Health System, 1E Kent Ridge Road, Level 7 NUHS Tower Block, Singapore 119228; ephcc@nus.edu.sg.

ever, these axes do not necessarily coincide. Thibos et al.<sup>20</sup> proposed a power vector approach, which converts clinical notations of cylinder power and cylinder axis to power vectors, allowing for the incorporation of the magnitude and axis of all forms of astigmatism in statistical analyses. Thus, it provides a sufficient and accurate statistical approach for astigmatism<sup>21</sup> and facilitates accurate assessment even when both the direction and the magnitude of astigmatism change simultaneously.

In the present study, we used power vector methods to analyze age-related trends in refractive, corneal, and internal astigmatism and assessed the association between internal astigmatism and different types of lens opacity in an elderly Chinese population aged 65 years and older in Taiwan.

## METHODS

### Study Population

This analysis was a part of the population-based Shihpai Eye Study. Details on the design and methods of the Shihpai Eye Study have been described elsewhere.<sup>5</sup> Briefly, it was conducted among noninstitutionalized residents aged 65 years and older in Shihpai, Taipei, Taiwan between July 1999 and December 2000. The government household registration system served as the sampling base for the study. Of 2045 randomly selected eligible persons, 1361 (66.6%) participated in ocular examinations. The study protocol was approved by the institutional review board and adhered to the provisions of the Declaration of Helsinki of the World Medical Association regarding scientific research on human subjects.

Of the 1361 participants (2722 eyes), we excluded 174 right eyes and 174 left eyes because of previous cataract surgery and 79 right eyes and 62 left eyes with refractive errors that could not be appropriately measured because of dense cataract, corneal or media opacity, bulbar atrophy, or other reasons. This left 1190 subjects who had at least one phakic eye with data on refractive errors (1108 right and 1115 left eyes) for prevalence analysis. Comparing the subjects included in the prevalence analysis with those excluded, we found that, on average, included subjects were younger (71.8 vs. 75.2 years;  $P < 0.001$ ), included more men (62% vs. 52%;  $P = 0.017$ ), and attained education levels of senior high school or higher (38 vs. 29%;  $P = 0.013$ ).

Keratometry was not performed initially but was added to the study protocol from August 1999 onward. Therefore, 57 (4.8%) of the 1190 subjects did not have data on corneal dioptric power. Additionally, keratometry could not be reliably performed on 13 right eyes and 12 left eyes. Therefore, power vector analysis was based on 1038 right and 1046 left eyes whose data on corneal dioptric power were available.

### Examination Procedure

A home interview with a structured questionnaire was administrated before the ocular examinations. The questionnaire collected information on demographic data, personal medical history, and lifestyle. Those who were interviewed were invited to the study hospital for a series of ocular examinations according to standardized protocols that included visual acuity (presenting and best-corrected) measurement with Snellen charts at a distance of 6 m, autorefraction and keratometry with an autokeratorefractometer (RK-8100; Topcon, Tokyo, Japan), noncontact tonometry (CT-60; Topcon), slit lamp biomicroscopy (model BQ900; Haag-Streit, Bern, Switzerland), and indirect ophthalmoscopy (model 12500; Welch-Allyn, Skaneateles Falls, NY). For autorefraction and keratometry, we took at least five consistent measurements and obtained an average of these readings. Because of the age of the study population, cycloplegia was not used. The result of autorefraction was used as a starting point for a subsequent subjective refraction. The refractive correction that achieved the best-corrected visual acuity in each eye was recorded and used for the analysis. We calculated corneal astigmatism based on the autokeratometry reading

using a corneal refractive index of 1.3375. This takes into account the negative refractive power of the posterior corneal surface. Corneal astigmatism was expressed as the correcting cylinder that would be combined with the corneal power to give zero astigmatism. Cylindrical power was calculated as the minimum corneal power minus the maximum corneal power, and cylindrical axis was set at the corneal meridian of minimum corneal power.<sup>22</sup> Lens opacity was graded using slit lamp biomicroscopy with the modified Lens Opacity Classification System (LOCS) III.<sup>23</sup> Under this system, nuclear opacity was classified in increasing severity as grades 1 to 6 (in increments of 1.0), and cortical and posterior subcapsular opacities were classified as grades 1 to 5.

## Definitions

For the prevalence analysis, astigmatism (minus cylinder format) was defined as cylinder  $\leq -0.75$  diopters (D) without reference to the axis. For the vectorial analysis, we converted the refractive and corneal astigmatism from the spherocylinder notation to power vector notation by applying a Fourier transformation using the following equations<sup>20</sup>:

$$J_0 = -\frac{C}{2} \times \cos 2\alpha$$

$$J_{45} = -\frac{C}{2} \times \sin 2\alpha$$

where  $C$  is negative cylindrical power and  $\alpha$  is cylindrical axis.  $J_0$  refers to cylinder power set at orthogonally 90° and 180° meridians, representing Cartesian astigmatism. Positive values of  $J_0$  indicate WTR astigmatism, and negative values of  $J_0$  indicate ATR astigmatism.  $J_{45}$  refers to a cross-cylinder set at 45° and 135°, representing oblique astigmatism. The power vector conversion was performed for both refractive and corneal astigmatism. Internal astigmatism was calculated as refractive minus corneal power values.<sup>24</sup> This calculation is essentially based on a two-refracting-component schematic model of the eye in which the principal planes of cornea and internal optics are coincident. Because a refractive index of 1.3375 is used, the keratometry has taken both anterior and posterior corneal surfaces into account. Therefore, in our study, internal astigmatism refers to the components of refractive astigmatism behind the cornea (i.e., ocular optical elements behind the cornea). In interpreting astigmatism using power vector values, it may be useful to consider that cylindrical power is defined as two times the square root of the sum of  $J_0^2$  and  $J_{45}^2$ . Thus, for example, an eye with zero  $J_{45}$  and 0.5 D of  $J_0$  in power vector notation corresponds to 1.0 D of cylinder in conventional notation.

## Statistical Analysis

Data on both eyes were included in our analysis because the magnitudes of correlation in refractive cylindrical ( $\rho = 0.53$ ) and corneal cylindrical ( $\rho = 0.63$ ) powers between right and left eyes were moderate only. The crude prevalences of astigmatism were calculated and were age- and sex-standardized according to the 1999 Taiwan population<sup>25</sup> to obtain a more accurate estimate of the actual prevalence. Linear regression models were used to assess the associations with astigmatism. We calculated the proportion of the variation in astigmatism explained by independent variables using  $r^2$  and then using partial  $r^2$  when more than two independent variables were involved in regression models. When data from both eyes were included in the regression models, generalized estimation equations (GEE) were used to account for the correlation between both eyes of individual participants.<sup>26</sup> Because the effects from  $J_{45}$  offset when both eyes were included in the regression models,<sup>27</sup> we performed the regression analysis of  $J_{45}$  on the data from right eyes and left eyes separately. In addition, to better explore nonlinear astigmatism-age association, we used restricted cubic splines with

**TABLE 1.** Prevalences of Refractive Astigmatism ( $\leq -0.75$  D) in the Shihpai Eye Study by Eye, Sex, and Age Groups ( $n = 1190^*$ )

Age Group (y)	Right Eye ( $n = 1108$ )			Left Eye ( $n = 1115$ )		
	Men	Women	Total	Men	Women	Total
Overall	509 (73.9)	300 (71.6)	809 (73.0)	510 (74.1)	342 (80.1)	852 (76.4)
65-69	180 (70.6)	108 (62.1)	288 (67.1)	176 (67.4)	133 (75.6)	307 (70.7)
70-74	193 (72.0)	312 (75.1)	312 (75.1)	206 (75.5)	126 (81.3)	332 (77.6)
75-79	92 (78.6)	147 (77.8)	147 (77.8)	90 (84.1)	62 (83.8)	152 (84.0)
80+	44 (89.8)	18 (75.0)	62 (84.9)	40 (80.0)	21 (95.5)	61 (84.7)
<i>P</i> for trend	0.005	0.009	<0.001	0.001	0.017	<0.001

Data are number of subjects with astigmatism (prevalence, %).  
 \* 1190 subjects had at least one phakic eye with data on refraction.

equally spaced knots at the 5th, 35th, 65th, and 95th percentiles of the age distribution.<sup>28,29</sup> All data analyses were performed with a commercial statistical software package (Stata 10.0; Stata Corp., College Station, TX). The threshold for statistical significance was set at  $P < 0.05$ .

**RESULTS**

The prevalences of refractive astigmatism (cylinder  $\leq -0.75$ D) by sex and age groups in the 1190 participants (mean age,  $71.8 \pm 4.8$  years) are shown in Table 1. The overall crude rate of astigmatism in the right eyes was 73.0%, and the age- and sex-standardized rate was 74.2% (95% confidence interval [CI], 71.6%-76.8%), and the overall crude rate in the left eyes was 76.4%, with the age- and sex-standardized rate of 77.4% (95% CI, 74.9%-79.9%). The prevalence increased significantly with age for both men and women in either eye ( $P < 0.05$  for all).

Table 2 summarizes the refractive and corneal power vectors by eye and age groups. With increasing age, the vector values in both refractive and corneal  $J_0$  changed toward more negative ( $P < 0.001$  for both). The distribution of refractive  $J_0$  versus refractive  $J_{45}$  by age groups is also shown in Figure 1. With increasing age, refractive  $J_0$  in either right or left eyes shifted toward negative, indicating a trend toward ATR. Refractive  $J_{45}$  increased with age in the right eyes ( $P < 0.001$ ) and decreased slightly with age in the left eyes ( $P = 0.012$ ) (Table 2, Fig. 1).

The associations among refractive  $J_0$ , corneal  $J_0$ , and internal  $J_0$  with age by restricted cubic splines are presented in Figure 2. We noted the changes in refractive  $J_0$  and corneal  $J_0$  with age were almost parallel after approximately 70 years of age. Linear regression analysis showed that refractive  $J_0$  significantly changes with age (regression coefficient,  $\beta = -0.082$  D per 5 years;  $P < 0.001$ , corresponding to approximately  $-0.16$  D of cylinder in conventional notation for eyes with near-zero  $J_{45}$ ). After adjustments for corneal  $J_0$ , the association between refractive  $J_0$  and age was much weaker ( $P = 0.054$ ). Corneal  $J_0$  alone accounted for more than half ( $r^2 = 54\%$ ) of the variability in refractive  $J_0$ . For internal  $J_0$ , we did not observe apparent age trends (Table 2, Fig. 2). Figure 3 shows the associations of refractive  $J_{45}$ , corneal  $J_{45}$ , and internal  $J_{45}$  with age by restricted cubic splines. The associations of refractive and corneal  $J_{45}$  with age tended to be stronger in the right eyes than in the left eyes (see also Table 2).

The distribution of lens opacity grades can be found in Supplementary Table S1 (<http://www.iovs.org/lookup/suppl/doi:10.1167/iovs.11-7641/-/DCSupplemental>). Table 3 presents the association between internal  $J_0$  and the severity of lens opacity. In the multiple linear regression analysis, cortical opacity was significantly ( $P = 0.025$ ) associated with internal  $J_0$  while controlling for age, sex, and the other two types of lens opacity, suggesting independent effects of cortical opacity on internal  $J_0$ . For one grade higher in cortical opacity, internal  $J_0$  changed by 0.022D in vector value. However, cortical opacity

**TABLE 2.** Vector Values of the Refractive, Corneal, and Internal Astigmatism by Eye and Age Groups

Eye and Age Groups (y)	Refractive Astigmatism		Corneal Astigmatism		Internal Astigmatism	
	$J_0$ (D)	$J_{45}$ (D)	$J_0$ (D)	$J_{45}$ (D)	$J_0$ (D)	$J_{45}$ (D)
<b>Right Eye (<math>n = 1038</math>)*</b>						
Total	$-0.42 \pm 0.54$	$0.09 \pm 0.34$	$-0.17 \pm 0.43$	$0.04 \pm 0.26$	$-0.25 \pm 0.36$	$0.06 \pm 0.27$
65-69	$-0.34 \pm 0.53$	$0.04 \pm 0.31$	$-0.11 \pm 0.41$	$0.00 \pm 0.27$	$-0.24 \pm 0.32$	$0.04 \pm 0.26$
70-74	$-0.41 \pm 0.51$	$0.12 \pm 0.33$	$-0.18 \pm 0.43$	$0.05 \pm 0.22$	$-0.23 \pm 0.35$	$0.07 \pm 0.26$
75-79	$-0.56 \pm 0.56$	$0.12 \pm 0.37$	$-0.25 \pm 0.47$	$0.05 \pm 0.26$	$-0.31 \pm 0.43$	$0.07 \pm 0.29$
80+	$-0.56 \pm 0.59$	$0.22 \pm 0.40$	$-0.39 \pm 0.43$	$0.11 \pm 0.34$	$-0.26 \pm 0.45$	$0.11 \pm 0.35$
<i>P</i> for trend	<0.001	<0.001	<0.001	0.001	0.117	0.025
<b>Left Eye (<math>n = 1046</math>)*</b>						
Total	$-0.44 \pm 0.52$	$-0.02 \pm 0.36$	$-0.17 \pm 0.43$	$0.01 \pm 0.23$	$-0.26 \pm 0.37$	$-0.04 \pm 0.27$
65-69	$-0.36 \pm 0.51$	$-0.01 \pm 0.28$	$-0.10 \pm 0.41$	$0.01 \pm 0.19$	$-0.26 \pm 0.36$	$-0.02 \pm 0.23$
70-74	$-0.44 \pm 0.51$	$-0.02 \pm 0.35$	$-0.19 \pm 0.43$	$0.02 \pm 0.28$	$-0.25 \pm 0.35$	$-0.04 \pm 0.27$
75-79	$-0.57 \pm 0.58$	$-0.06 \pm 0.35$	$-0.29 \pm 0.47$	$0.00 \pm 0.22$	$-0.28 \pm 0.41$	$-0.06 \pm 0.30$
80+	$-0.56 \pm 0.59$	$-0.10 \pm 0.37$	$-0.30 \pm 0.38$	$-0.01 \pm 0.24$	$-0.26 \pm 0.36$	$-0.09 \pm 0.35$
<i>P</i> for trend	<0.001	0.012	<0.001	0.352	0.813	0.025

\* 1038 of the 1108 right eyes and 1046 of the 1115 eyes have data on corneal astigmatism.

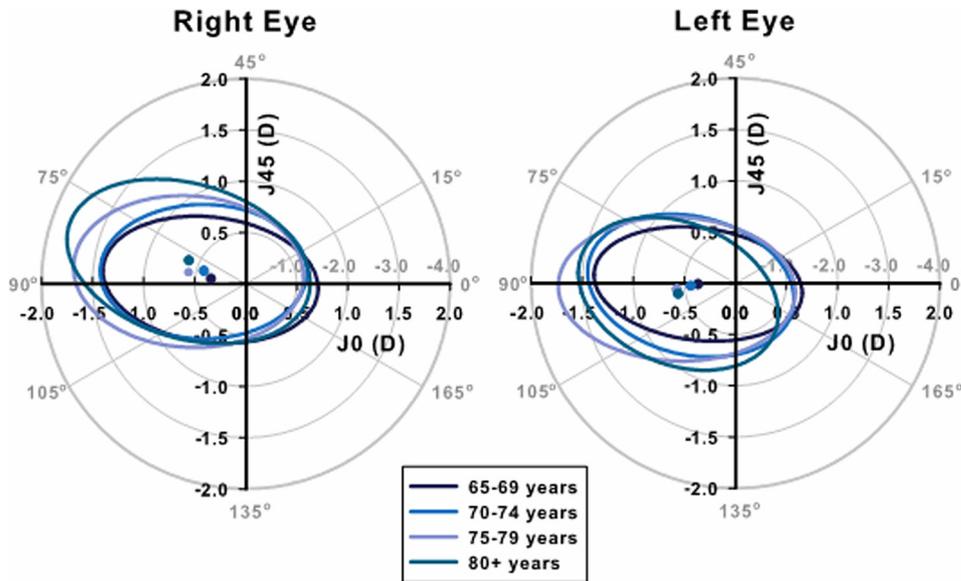


FIGURE 1. Distributions of refractive  $J_0$  and refractive  $J_{45}$  by eye and age groups. The ellipses are the 95% bivariate confidence intervals, and the solid circles inside the ellipses represent the mean vectors. The gray concentric circles and gray tick labels represent the clinical cylinder power (in diopters), and the azimuthal ticks indicate the clinical axes.

explained only a small proportion of the variation in internal  $J_0$  (partial  $r^2 = 0.28\%$ ). There were no significant associations between internal  $J_0$  and the other two types of lens opacity. In the multiple linear regression analysis, internal  $J_{45}$  was not associated with any type of lens opacity (Table 4).

DISCUSSION

Astigmatism and age-related cataract are two of the most common ocular conditions in the elderly. In this population-based study, we quantified the change in astigmatism with age in an elderly Taiwanese population. The prevalence of astigmatism increased, and changes toward ATR were noted in both refractive and corneal components. We also found that the severity of cortical opacity was associated with internal  $J_0$ .

In our study, approximately three quarters of participants aged 65 years and older had astigmatism. It is difficult to accurately compare the prevalences among studies because of varied measurements, discrepancies in definitions, and diverse age groups across studies. However, we compared our findings with those reported for populations in which the age distribution was similar and that used definitions comparable to those used in the present study. Our estimates of prevalence were comparable to those reported in the Tajimi Study of a Japanese population<sup>2</sup> (75.9% at 70–80 years, 89.2% at >80 years, astigmatism < -0.50 D), the Liwan Eye Study in a Chinese population<sup>1</sup> (61.8% at 70–79 years, 69.3% at 80–93 years, astigma-

tism < -0.75 D), and the Reykjavik Eye Study in a Northern European population<sup>13</sup> (approximately 75.5% at 75–79 years, astigmatism < -0.75 D) but higher than that in the Singapore Malay Eye Study<sup>30</sup> (58.5%–67.1% at 70–80 years, astigmatism < -0.50 D).

The details of the reasons for the change in refractive astigmatism toward ATR with age remain unclear. In the present study, in addition to refractive  $J_0$ , corneal  $J_0$  alone accounted for a large proportion (54%) of the variability in refractive  $J_0$ . Moreover, the age-related trend in the estimated internal  $J_0$  was weak. These data show that the ATR changes in refractive astigmatism with age were attributed primarily to the age-related changes in corneal topography. However, the underlying biomechanical causes of the trend toward ATR in corneal astigmatism remain to be fully elucidated and are subject to speculation. The age-related ATR shift may be attributed to changes in the corneal structure itself or to external factors, and we believe that both play a role. It has been shown that increasing age is associated with a decrease in corneal diameter that is more pronounced horizontally than vertically, causing an ATR shift in corneal astigmatism.<sup>31</sup> Furthermore, a variety of aging changes in the corneal structures have been reported, including growth of collagen fibrils in the stroma,<sup>32</sup> increased thickness of Descemet membrane,<sup>33</sup> and degeneration of endothelial cells. These biomechanical changes might alter collagen orientation and affect the elasticity and rigidity of the cornea,

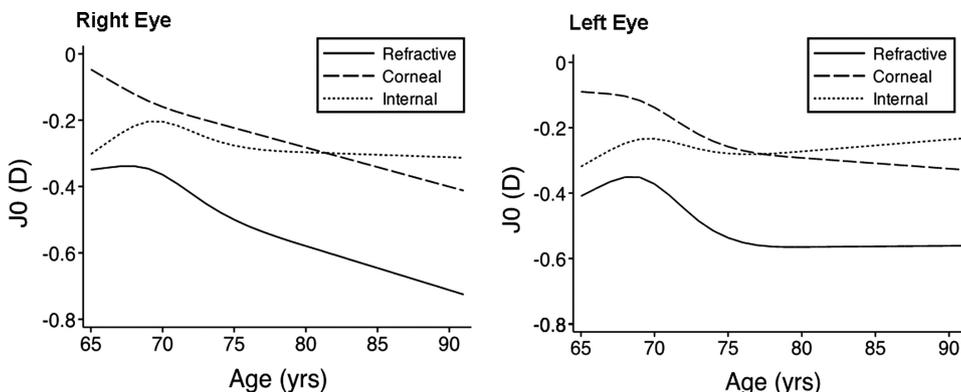


FIGURE 2. Restricted cubic splines exploring the relationship between  $J_0$  and age in right eyes and left eyes.

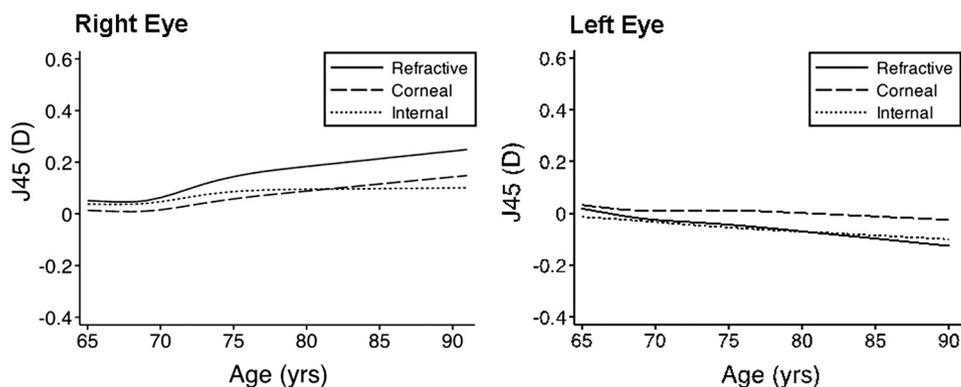


FIGURE 3. Restricted cubic splines exploring the relationship between  $J_{45}$  and age in right eyes and left eyes.

leading to ATR shifts in corneal astigmatism. Other external factors have been proposed as well. Diminished eyelid tension caused by age-related dermatochalasis may lead to a relative flattening of the cornea in the vertical meridian and steeper corneal curvature in the horizontal meridian, resulting in ATR shifts in the corneal refractive state.<sup>34</sup>

In our study, compared with refractive and corneal astigmatism, the change in internal astigmatism with age was relatively small. Previous studies have reported that lenticular astigmatism held constant at approximately 0.5 D in children and adults,<sup>35,36</sup> and astigmatism of lenticular origin appeared to have little effect on total astigmatism in young normal eyes.<sup>37</sup> Similarly, we found that internal  $J_0$  remained constant at  $-0.25$  D (in vector value) in elderly persons.

The nature of cataract-induced astigmatism is not well understood, and the effects of types and severity of age-related cataract on internal astigmatism warrant more exploration. In a small clinic-based study, Pesudovs et al.<sup>17</sup> reported that persons with cortical cataract showed larger refractive astigmatic shifts than subjects with clear lenses. Unlike that report, we estimated internal astigmatism, instead of using refractive astigmatism, to account for the effects of corneal components and to obtain more precise exploration of the association between astigmatic changes and different cataract types. Additionally, we examined the effects of cataract severity on internal astigmatism. We found that the severity of cortical opacity was statistically significantly associated with internal  $J_0$ , with a change toward WTR astigmatism, although the magnitude of the change was small. This suggests that, in patients with cortical cataract, lens-induced astigmatism may to some extent offset corneal ATR changes with age. However, the mechanism by which cortical lens opacity induces WTR astigmatism change is unclear. It is likely to be caused by asymmetrical refractive index changes within different parts of the lens cortex,<sup>38</sup> causing comalike aberrations and astigmatic shifts.<sup>39</sup> It has been suggested that the negative axis of astigmatism may correspond to the axis of a cortical

spoke.<sup>17</sup> Whether the cortical spoke develops and progresses more often in the horizontal than the vertical meridian, thus inducing WTR change, requires further investigation.

We did not find a significant association between the severity of lens opacity and internal  $J_{45}$ . In the Meiktila Eye Study<sup>3</sup> conducted in rural Myanmar, refractive astigmatism was significantly higher in persons with nuclear opacity. It is well known that nuclear opacities may lead to myopic shifts through changes in the lenticular refractive index, but whether nuclear opacity induces changes in internal astigmatism remains to be elucidated.

We acknowledge certain limitations of our study. First, it had a cross-sectional design. Thus, we were unable to draw conclusions on lifetime longitudinal changes of astigmatism with age. Second, a small proportion (4.8%) of our study population did not have measurements on corneal astigmatism. We believe, however, that this should not have caused any significant differential bias in our results. Third, lens opacity was graded using LOCS III in increments of 1.0 rather than 0.1, making individual grades coarser. However, the validity of the regressions might not have been adversely affected because the sample size was large. Finally, the association between cortical lens opacity and internal astigmatism was weak despite its being statistically significant. Other unmeasured or unknown factors may have greater effects, and this warrants further studies. On the other hand, we excluded subjects who had previously undergone cataract surgery from the analysis. Thus, we might have lost some of the more informative subjects.

In conclusion, astigmatism is highly prevalent in the elderly Chinese population in Taiwan. There is a trend toward ATR with increasing age in corneal astigmatism, with the consequence of corresponding changes in refractive astigmatism. The severity of cortical cataract is associated, albeit weakly, with internal  $J_0$ . Given that the aging population is growing rapidly, the nature and trends of astigmatism with age and the association between internal astigmatism and lens opacity sug-

TABLE 3. Multivariate Linear Regression Models Assessing the Association of Internal  $J_0$  with Lens Opacity ( $n = 2084$  eyes)

Factors	$\beta^*$ (95% CI)	P	Partial $r^2$ (%)
Nuclear opacity	-0.015 (-0.03 to 0.005)	0.146	0.15
Cortical opacity	0.022 (0.00 to 0.042)	0.025	0.28
Posterior subcapsular opacity	-0.015 (-0.04 to 0.012)	0.277	0.06
Age (5 years older)	-0.009 (-0.02 to 0.010)	0.358	0.04
Sex (female vs. male)	-0.061 (-0.098 to -0.024)	0.002	0.63

\*  $\beta$ , regression coefficient; for lens opacity, it represents the change in internal  $J_0$  for one grade higher in each type of lens opacity, controlling for age and sex, and the other two types of lens opacity.

TABLE 4. Multivariate Linear Regression Models Assessing the Association of Internal J<sub>45</sub> with Lens Opacity by Eye

Factors	$\beta^*$ (95% CI)	P	Partial $r^2$ (%)
<b>Right Eyes (n = 1038)</b>			
Nuclear opacity	-0.006 (0.026 to 0.013)	0.532	0.04
Cortical opacity	0.001 (-0.019 to 0.020)	0.991	0.01
Posterior subcapsular opacity	-0.004 (-0.031 to 0.023)	0.755	0.01
Age (5 years older)	0.025 (0.007 to 0.044)	0.007	0.71
Sex (female vs. male)	0.033 (-0.003 to 0.068)	0.069	0.32
<b>Left Eyes (n = 1046)</b>			
Nuclear opacity	0.002 (-0.017 to 0.021)	0.829	0.01
Cortical opacity	0.001 (-0.018 to 0.019)	0.929	0.01
Posterior subcapsular opacity	-0.016 (-0.041 to 0.009)	0.217	0.15
Age (5 years older)	-0.020 (-0.037 to -0.002)	0.030	0.45
Sex (female vs. male)	-0.046 (-0.080 to -0.013)	0.007	0.69

\*  $\beta$ , regression coefficient; for lens opacity, it represents the change in internal J<sub>45</sub> for one grade higher in each type of lens opacity, controlling for age and sex, and the other two types of lens opacity.

gested by our study are noteworthy and may help provide knowledge about refraction-related and cataract-related eye care in the elderly. The age-related changes in astigmatism may be taken into consideration when performing refractive surgery or cataract surgery in the elderly to obtain an enduring refractive status. It is also helpful in predicting long-term outcomes of refractive surgeries and refractive changes after cataract surgery in the elderly.

## References

- He M, Huang W, Li Y, et al. Refractive error and biometry in older Chinese adults: the Liwan Eye Study. *Invest Ophthalmol Vis Sci.* 2009;50:5130-5136.
- Sawada A, Tomidokoro A, Araie M, et al. Refractive errors in an elderly Japanese population: the Tajimi Study. *Ophthalmology.* 2008;115:363-370.e3.
- Gupta A, Casson RJ, Newland HS, et al. Prevalence of refractive error in rural Myanmar: the Meiktila Eye Study. *Ophthalmology.* 2008;115:26-32.
- Raju P, Ramesh SV, Arvind H, et al. Prevalence of refractive errors in a rural South Indian population. *Invest Ophthalmol Vis Sci.* 2004;45:4268-4272.
- Cheng CY, Hsu WM, Liu JH, Tsai SY, Chou P. Refractive errors in an elderly Chinese population in Taiwan: the Shihpai Eye Study. *Invest Ophthalmol Vis Sci.* 2003;44:4630-4638.
- Guzowski M, Wang JJ, Rochtchina E, Rose KA, Mitchell P. Five-year refractive changes in an older population: the Blue Mountains Eye Study. *Ophthalmology.* 2003;110:1364-1370.
- Gudmundsdottir E, Arnarsson A, Janasson F. Five-year refractive changes in an adult population: Reykjavik Eye Study. *Ophthalmology.* 2005;112:672-677.
- Hashemi H, Fotouhi A, Mohammad K. The age- and gender-specific prevalence of refractive errors in Tehran: the Tehran Eye Study. *Ophthalmic Epidemiol.* 2004;11:213-225.
- Lam AK, Chan CC, Lee MH, Wong KM. The aging effect on corneal curvature and the validity of Javal's rule in Hong Kong Chinese. *Curr Eye Res.* 1999;18:83-90.
- Ferrer-Blasco T, Gonzalez-Mejome JM, Montes-Mico R. Age-related changes in the human visual system and prevalence of refractive conditions in patients attending an eye clinic. *J Cataract Refract Surg.* 2008;34:424-432.
- Li Z, Sun D, Cui H, et al. Refractive error among the elderly in rural Southern Harbin, China. *Ophthalmic Epidemiol.* 2009;16:388-394.
- Yekta AA, Fotouhi A, Khabazkhoob M, et al. The prevalence of refractive errors and its determinants in the elderly population of Mashhad, Iran. *Ophthalmic Epidemiol.* 2009;16:198-203.
- Gudmundsdottir E, Jonasson F, Jonsson V, et al. "With the rule" astigmatism is not the rule in the elderly. Reykjavik Eye Study: a population based study of refraction and visual activity in citizens of Reykjavik 50 years and older: Iceland and Japan Co-Working Study Groups. *Acta Ophthalmol Scand.* 2000;78:642-646.
- Asano K, Nomura H, Iwano M, et al. Relationship between astigmatism and aging in middle-aged and elderly Japanese. *Jpn J Ophthalmol.* 2005;49:127-133.
- Wheelock A. Cataract and against-the-rule astigmatism. *Am J Optom Arch Am Acad Optom.* 1941;18:489-492.
- Lyle W. Changes in astigmatism associated with the development of cataract. *Am J Optom Arch Am Acad Optom.* 1951;28:551-559.
- Pesudovs K, Elliott DB. Refractive error changes in cortical, nuclear, and posterior subcapsular cataracts. *Br J Ophthalmol.* 2003;87:964-967.
- Brown NA. The morphology of cataract and visual performance. *Eye.* 1993;7:63-67.
- Tint NL, Jayaswal R, Masood I, Maharajan VS. Rapidly progressive idiopathic lenticular astigmatism. *J Cataract Refract Surg.* 2007;33:333-335.
- Thibos LN, Wheeler W, Horner D. Power vectors: an application of Fourier analysis to the description and statistical analysis of refractive error. *Optom Vis Sci.* 1997;74:367-375.
- Miller JM. Clinical applications of power vectors. *Optom Vis Sci.* 2009;86:599-602.
- Tong L, Carkeet A, Saw SM, Tan DT. Corneal and refractive error astigmatism in Singaporean schoolchildren: a vector-based Javal's rule. *Optom Vis Sci.* 2001;78:881-887.
- Chylack LT Jr, Wolfe JK, Singer DM, et al. The Lens Opacities Classification System III. *Arch Ophthalmol.* 1993;111:831-836.
- Muñoz-Escrivá L, Furlan WD. Statistical analysis when dealing with astigmatism: assessment of different spherocylindrical notations. *Ophthalmic Epidemiol.* 2001;8:27-37.
- 1999 Taiwan-Fukien Demographic Book, Republic of China. Taipei, Taiwan: Ministry of Interior, Republic of China; 2000.
- Zeger SL, Liang KY. Longitudinal data analysis for discrete and continuous outcomes. *Biometrics.* 1986;42:121-130.
- Haegerstrom-Portnoy G, Schneck ME, Brabyn JA, Lott LA. Development of refractive errors into old age. *Optom Vis Sci.* 2002;79:643-649.
- Harrell F, Lee K, Pollock B. Regression models in clinical studies: determining relationships between predictors and response. *J Natl Cancer Inst.* 1988;80:1198-1202.
- Greenland S. Dose-response and trend analysis in epidemiology: alternatives to categorical analysis. *Epidemiology.* 1995;6:356-365.
- Saw SM, Chan YH, Wong WL, et al. Prevalence and risk factors for refractive errors in the Singapore Malay Eye Survey. *Ophthalmology.* 2008;115:1713-1719.
- Leighton DA, Tomlinson A. Changes in axial length and other dimensions of the eyeball with increasing age. *Acta Ophthalmol.* 1972;50:815-826.

32. Daxer A, Misof K, Grabner B, Ettl A, Fratzl P. Collagen fibrils in the human corneal stroma: structure and aging. *Invest Ophthalmol Vis Sci.* 1998;39:644-648.
33. Faragher RG, Mulholland B, Tuft SJ, Sandeman S, Khaw PT. Aging and the cornea. *Br J Ophthalmol.* 1997;81:814-817.
34. Goss DA. Meridional analysis of with-the-rule astigmatism in Oklahoma Indians. *Optom Vis Sci.* 1989;66:281-287.
35. Dobson V, Miller JM, Harvey EM. Corneal and refractive astigmatism in a sample of 3- to 5-year-old children with a high prevalence of astigmatism. *Optom Vis Sci.* 1999;76:855-860.
36. Grosvenor T, Ratnakaram R. Is the relation between keratometric astigmatism and refractive astigmatism linear? *Optom Vis Sci.* 1990;67:606-609.
37. Shankar S, Bobier WR. Corneal and lenticular component of total astigmatism in a preschool sample. *Optom Vis Sci.* 2004;81:536-542.
38. Planten JT. Changes in the refraction in the adult eye due to changing refractive indices of the layers of the lens. *Ophthalmologica.* 1981;183:86-90.
39. Kuroda T, Maeda N, Oshika T, Hirohara Y, Mihashi T. Wavefront analysis of higher-order aberrations in patients with cataract. *J Cataract Refract Surg.* 2002;28:438-444.