Preschool Children Exhibit Evident Compensatory Role of Internal Astigmatism in Distribution of Astigmatism: The Nanjing Eye Study

Zijin Wang,1 Dan Huang,1 Xuejuan Chen,1 Hui Zhu,1 Qigang Sun,1 Yue Wang,1 Xiaohan Zhang,1 Yue Wang,2 Leili Zhai,2 Chenyang Wang,2 and Hu Liu1

1Department of Ophthalmology, The First Affiliated Hospital with Nanjing Medical University, Nanjing, China
2The Fourth School of Clinical Medicine of Nanjing Medical University, Nanjing, China

Correspondence: Hu Liu, Department of Ophthalmology, The First Affiliated Hospital with Nanjing Medical University, 300 Guangzhou Road, Nanjing 210029, China; liuhu66@njmu.edu.cn.

PURPOSE. To determine the prevalence and associated risk factors for total, corneal, and residual astigmatism and to evaluate the relations between components of astigmatism in Chinese preschool children.

METHODS. In the population-based, cross-sectional Nanjing Eye Study, children were measured for noncycloplegic refractive error using an autorefractor and for biometric parameters using an optical low-coherent reflectometry. Data from right eyes were analyzed to calculate the prevalence of astigmatism using various cutpoints (0.5, 1.0, and 1.5 diopters [D]) and for determining risk factors using logistic regression models. Relations between astigmatism components were assessed using Spearman correlation coefficients (ρ).

RESULTS. Of 1817 children (mean ± SD of age: 54.8 ± 3.5 months, 54.2% male), the median (1st and 3rd quartile) of total, corneal, and residual astigmatism (vectorial difference between total and corneal astigmatism) was −0.25 (−0.50, 0), −1.06 (−1.49, −0.72), and −0.92 (−1.23, −0.62) D and their prevalence rate 1.0 D or more was 14.2%, 56.1%, and 44.2%, respectively. With-the-rule was the most common type in total astigmatism (75.2%) and in corneal astigmatism (88.2%) while against-the-rule was predominant in residual astigmatism (75.6%). A negative correlation was found between corneal J60 and internal J60 (ρ = −0.74, P < 0.001) and between corneal J45 and internal J45 (ρ = −0.87, P < 0.001). Based on compensation factor (CF), defined as the minus ratio of internal astigmatism (vectorial difference between total and anterior corneal astigmatism) and anterior corneal astigmatism, internal J60 compensated for total J60 in varying degrees (CF: 0.1–2) in 91.5% cases, while that percentage for J45 component was 77.2%. In univariate logistic regression model, older age was significantly associated with total astigmatism (odds ratio [OR] = 0.96 for per-month increase, P = 0.03), and larger axial length–corneal radius ratio was significantly associated with higher risk of residual astigmatism (OR = 2.28 for per unit increase, P = 0.03).

CONCLUSIONS. The compensatory role of internal astigmatism on reducing corneal astigmatism was prominent in preschool children. Larger axial length–corneal radius ratio was significantly associated with higher risk of residual astigmatism.

Keywords: astigmatism, prevalence, compensation factor, risk factor

Astigmatism is the condition that prevents light rays from focusing at a single point in the eye, leading to the blurred vision at near or far distance.1 Astigmatism, an important type of refractive error, is a clinical and public health problem.2 Astigmatism, if uncorrected, can lead to continuous blurred vision experienced at all distances; thus, increases the risk of amblyopia.3 Orientation-dependent visual deficits caused by uncorrected astigmatism cannot be reversed if optical correction is delayed.4 In addition, some researchers suggest that astigmatism may be associated with myopia progression.5,6

Two components of astigmatism have been independently measured and calculated, total astigmatism (TA) and corneal astigmatism (CA), to describe the characteristics of astigmatism. CA is calculated using an equivalent refractive index of 1.3375. Residual astigmatism (RA) is defined as the vectorial difference between TA and CA. Anterior corneal astigmatism (ACA) is defined as astigmatism of anterior corneal surface and calculated using corneal refractive index of 1.376. Internal astigmatism (IA) is defined as the vectorial difference between TA and ACA. Data on the distribution and relationship between these components of astigmatism are very limited, but they are important to help understand the development and progression of astigmatism in relation to corneal, refractive, and cataract surgery.7

The purpose of this study was to describe the characteristics of astigmatism and its components in Chinese preschool children including the prevalence for each component of astigmatism (TA, CA, and RA), the prevalence for each type of astigmatism (with-the-rule [WTR], against-the-rule [ATR], and oblique [OBL]), the relation between the magnitude of astigmatism components (TA, ACA, and IA), and the effects of sex, age, and the axial length–corneal radius ratio (AL/CR) on TA, CA, and RA.
METHODS

Study Design and Subjects

The Nanjing Eye Study (NES) is a population-based cohort study, designed to longitudinally observe the onset and progression of childhood ocular diseases in eastern China. The study was approved by the institutional review board in The First Affiliated Hospital with Nanjing Medical University and was conducted in accordance with the tenets of the Declaration of Helsinki. Written consent was obtained from the parents or guardians of all children.

The study population for the present study consisted of 48- to 60-month-old children enrolled in kindergarten in the Yuhuatai District and born between September 2011 and August 2012. Eye examination results presented were obtained from September to November of 2016.

Eye Examination

Two ophthalmologists and two optometrists specialized in pediatric eye care performed comprehensive eye examinations following the similar standardized study protocols described in the multiethnic pediatric eye disease study (MEPDS). The noncycloplegic refractive status of both eyes of each participant was measured using an autorefractor (Cannon R-F10; Canon, Tokyo, Japan). The optic low-coherent reflectometer (LenStar LS-900; Haag-Streit AG, Koeniz, Switzerland) obtained biometric parameters, including central corneal thickness, corneal curvatures, anterior chamber depth, white-to-white corneal diameter, and axial length. Three consecutive scans were performed by the same experienced examiner. Scans were operated without pupil dilation, in a dimly lit room according to the manufacturers’ guidelines. Children first got seated, placed their chin on the chin rest with their forehead adhered to the headrest of the device. They were asked to stare into the central fixation dot in front of them and not to blink during the measurement. If the signal-to-noise ratio (SNR) was less than 2:1, another measurement was taken until reliable readings were achieved from each eye.

Definition

Astigmatism was defined as a cylinder magnitude worse than or equal to 0.5, 1.0, and 1.5 diopters (D), expressed as a negative cylinder form. ACA was calculated as the difference between the flattest and steepest corneal meridians of the anterior corneal surface power. IA was the vectorial difference between TA and ACA. ATB (cylinder axis 90°) was calculated by (1.3761/rr). This equivalent refractive index value 1.3375 takes the mean radius of curvature (mm). RA was the vectorial difference between TA and CA. The anterior corneal surface power was calculated by (1.3375/r). This equivalent refractive index value 1.3375 takes the mean radius of curvature (mm).

\[
J_{0r} = J_{0t} - J_{0c} \\
A_r = \arctan(J_{45r}/J_{0r})/2 \\
C_r = -2J_{0r}/\cos(2A_r)
\]

where \(J_{0r}, J_{0t}, \) and \(J_{0c}\) are \(J_0\) of RA, TA, and CA, respectively; \(J_{45r}, J_{45t}, \) and \(J_{45c}\) are \(J_{45}\) of RA, TA, and CA, respectively; \(A_r\) is the axis of RA, and \(C_r\) is the magnitude of RA. The denominator in the aforementioned formula should not be zero. If \(A_r\) is less than 0, then 180 was added to \(A_r\). Finally, \(C_r\) was transformed to minus format according to the cylinder conversion formula. Same is the vectorial composition and decomposition of ACA and IA.

CA, calculated with the simulated formula, has been used clinically to represent total corneal astigmatism, assuming a fixed posterior/anterior curvature ratio to estimate the contribution of posterior corneal power. For ease of comparison, TA, CA, and RA have been used to study their prevalence and risk factors. ACA is directly measured and transformed, thus IA includes posterior corneal astigmatism. ACA and IA are more appropriate when studying the internal compensation.

To study the compensation relation between ACA and IA, we introduced the compensation factor (CF), which was defined as the minus ratio of IA and ACA.13 45 and \(J_0\) and \(J_{45}\) were used to evaluate CF as following:

\[
CF_0 = -J_{0a}/J_{0t} \\
CF_{45} = -J_{45a}/J_{45t}
\]

where \(J_{0a}, J_{0t}\) are \(J_0\) of IA and ACA, respectively; \(J_{45a}, J_{45t}\) are \(J_{45}\) of IA and ACA, respectively. The compensation types were classified as following based on the calculated CF: (1) less than –0.1: same axis augmentation; (2) –0.1 to 0.1: no compensation; (3) 0.1 to 0.9: under-compensation; (4) 0.9 to 1.1: full compensation; (5) 1.1 to 2: overcompensation; and (6) greater than 2: opposite axis augmentation.

\(AL/\text{CR}\) was calculated as the axial length (mm) divided by the mean radius of curvature (mm).

Statistical Analysis

The Statistical Package for the Social Sciences (V13.0; IBM, Chicago, IL, USA) was employed for all the statistical analyses. Results were presented as mean ± SD for normally distributed data, median (1st and 3rd quartile) for skewed continuous measures, percentage and 95% CI for categoric measurements. Spearman correlation coefficient (\(\rho\)) was used to evaluate the relationships between magnitude of different types of astigmatism. \(AL/\text{CR}\) between boys and girls was compared using independent-samples t-test. Univariate logistic regression models were performed to evaluate the risk factors of each type of astigmatism (defined as their astigmatism magnitude ≥1.0 D).

All statistical tests were two-sided and \(P\) less than 0.05 was considered statistically significant.
RESULTS

Characteristics of Study Population

Among 2300 eligible preschoolers, 1986 (participation rate 86.4%) children were examined. As 169 children were uncooperative and no refraction measurements were obtained after repeated attempts, 1817 children (response rate 79.0%) had complete data from noncycloplegic autorefraction and corneal curvature in right eye, thus were included in this study. The mean (±SD) age was 54.9 ± 3.5 months and 984 (54.2%) participants were boys. Han nationality children (1800, 99.1%) constituted the majority of the population.

Magnitude and Prevalence of Astigmatism

The distribution of TA, CA, and RA were shown in Figure 1. The magnitude of TA indicated left skewness, meaning that most children having minimal or no astigmatism (61.6%, < 0.5 D). The distributions of CA and RA magnitude were also left skewed.

The median (1st and 3rd quartile) was −0.25 (−0.50, 0) D for TA, −1.06 (−1.49, −0.72) D for CA, and −0.92 (−1.25, −0.62) D for RA.

The prevalence of TA, CA, and RA using various cutpoints (≥0.5, ≥1.0, ≥1.5 D) were shown in Table 1. The prevalence rate of TA, CA, and RA 1.0 D or more was 14.2%, 56.1%, and 44.2%, respectively. TA and CA were predominantly WTR (75.2% and 88.2%), followed by OBL and a small proportion of ATR. By contrast, RA was mainly ATR (75.6%), followed by OBL and a small proportion of WTR.

Relationships Between Different Types of Astigmatism

When magnitude of TA, ACA, and IA was compared, ACA exceeds TA in 1702 (93.7%) children with median difference (1st and 3rd quartile) of 0.88 D (0.54, 1.24 D). Figure 2 shows the relationships between decomposers of TA and ACA. Figure 2A shows that most J0 values were below the line of equality, indicating that children have more ACA than TA along the Cartesian axes. Figure 2B shows that most J0 values were above the line of equality, suggesting most children had more TA than IA along the Cartesian axes. The correlation was 0.37 (P < 0.001) between total and anterior corneal J0 and 0.24 (P < 0.001) between total and internal J0. Negative correlation was found between anterior corneal and internal J0 (ρ = −0.74, P < 0.001). Figures 2C and 2D show that values for total and anterior corneal J45 distributed almost evenly above or below the line of equality, as well as values for total and internal J45. The correlation between total and anterior corneal J45 was 0.10 and 0.30 (both P < 0.001). Anterior corneal and internal J45 were negatively correlated (ρ = −0.87, P < 0.001).

Table 1. Distribution and Constitution of Total Astigmatism, Corneal Astigmatism, and Residual Astigmatism

<table>
<thead>
<tr>
<th>Astigmatism</th>
<th>WTR</th>
<th>ATR</th>
<th>OBL</th>
</tr>
</thead>
<tbody>
<tr>
<td>D ≥0.5</td>
<td>698</td>
<td>38.4 (36.2–40.6)</td>
<td>447</td>
</tr>
<tr>
<td>≥1</td>
<td>258</td>
<td>14.2 (12.6–15.8)</td>
<td>194</td>
</tr>
<tr>
<td>≥1.5</td>
<td>114</td>
<td>6.3 (5.2–7.4)</td>
<td>100</td>
</tr>
<tr>
<td>CA ≥0.5</td>
<td>1605</td>
<td>88.3 (86.8–89.8)</td>
<td>1310</td>
</tr>
<tr>
<td>≥1</td>
<td>1019</td>
<td>56.1 (53.8–58.4)</td>
<td>899</td>
</tr>
<tr>
<td>≥1.5</td>
<td>567</td>
<td>31.2 (29.1–33.3)</td>
<td>405</td>
</tr>
<tr>
<td>RA ≥0.5</td>
<td>1544</td>
<td>85.0 (83.4–86.6)</td>
<td>1078</td>
</tr>
<tr>
<td>≥1</td>
<td>803</td>
<td>44.2 (41.7–46.3)</td>
<td>727</td>
</tr>
<tr>
<td>≥1.5</td>
<td>221</td>
<td>12.2 (10.7–13.7)</td>
<td>15</td>
</tr>
</tbody>
</table>
The denominator of CF was zero for anterior corneal J0 in 40 children and for anterior corneal J45 in 98 children, thus were excluded from the calculation of CF. The compensation type of each child was displayed in Figure 3.

**Risk Factors**

AL/CR value ranged from 2.42 to 3.47 and was similar between boys and girls ($P = 0.80$). Sex, age, and AL/CR were evaluated as risk factors of astigmatism using univariate logistic regression. When astigmatism defined as 1 D or more, older age was significantly associated with lower risk of TA (odds ratio [OR] = 0.96 for every month increase, $P = 0.05$), while sex or AL/CR was not significantly associated with TA ($P = 0.26$ and $P = 0.38$, respectively). For CA, none of these factors was significantly associated ($P = 0.13$, $P = 0.09$, and $P = 0.12$ for sex, age, and AL/CR, respectively). For RA, larger AL/CR was significantly associated with higher risk of RA (OR = 2.28 per unit increase, $P = 0.03$), while neither sex nor age was significantly associated with RA ($P = 0.37$ and $P = 0.35$, respectively).

**DISCUSSION**

This study evaluated the prevalence of astigmatism at various cutpoints in Chinese preschool children. Results of prevalence of TA from previous studies on similar age population are shown in Table 2.5,7,16–27 These studies, varied in the children ethnicity and the definition of astigmatism, reported wide range of prevalence rate of astigmatism. The prevalence of TA in the present study was lower than that found in the Tohono O’odham Native American children (26.5%, >2D),16 concurring with the high prevalence of astigmatism in American Indian children. This difference has been attributed to the higher lid tension of the Mongoloid race. Although the Chinese are racially related to American Indians, results
suggest that difference exists among different nations of one race. The prevalence of astigmatism found in the present study was similar to that from the East Asian group, but higher than that from the South Asian, Middle Eastern, and European Caucasian groups. The prevalence of TA in Canadian children was similar to our result, while white children in the UK NICER study and African American and Hispanic children in the MEPDS had a higher prevalence of TA than those in the current study. When compared with studies of Chinese children, the TA prevalence in this study was similar to that of studies conducted in Hongkong, Xiamen city and countryside, Guangzhou, Singapore, and Guangzhou. The prevalence of TA was higher in the study in Singapore, Hongkong, and Weihai. The prevalence of TA was lower in two studies carried out in rural area of Heilongjiang and Shunyi District.

**Figure 3.** Scatter plots of corneal versus internal astigmatism (J₀ and J₄₅). Compensation types are showed in different colors.
<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Location</th>
<th>Age</th>
<th>Design</th>
<th>Sample Size</th>
<th>Astigmatism Definition, D</th>
<th>Astigmatism Prevalence</th>
<th>Predominant Type of Astigmatism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cowen and Bobier</td>
<td>2003</td>
<td>Oxford County, Canada</td>
<td>38–86 mo</td>
<td>Population-based</td>
<td>1162</td>
<td>≥0.25</td>
<td>76.1%</td>
<td>WTR (45%), ATR (40%), and then oblique (15%)</td>
</tr>
<tr>
<td>Huynh et al.</td>
<td>2006</td>
<td>Sydney, Australia</td>
<td>6–7 y</td>
<td>Population-based</td>
<td>Whole: 1724</td>
<td>≥0.5, ≥1</td>
<td>Whole: 22.6%, 4.8%</td>
<td>East Asian: 33.5%, 11.2%</td>
</tr>
<tr>
<td>Harvey et al.</td>
<td>2010</td>
<td>Tohono O’odham, America</td>
<td>4–5 y</td>
<td>Whole: 224</td>
<td>211</td>
<td>≥2</td>
<td>East Asian: 26.5%</td>
<td>East Asian: WTR-49.6%</td>
</tr>
<tr>
<td>O’Donoghue et al.</td>
<td>2011</td>
<td>Northern Ireland, UK</td>
<td>6–7 y</td>
<td>Population-based</td>
<td>392</td>
<td>≥1</td>
<td>29%</td>
<td>OBL 76%</td>
</tr>
<tr>
<td>Fozailoff et al.</td>
<td>2011</td>
<td>Los Angeles, America</td>
<td>48–59 mo</td>
<td>Population-based</td>
<td>Whole: 548</td>
<td>≥1.5</td>
<td>African American: 8.0%</td>
<td>WTR</td>
</tr>
<tr>
<td>Chan and Edwards</td>
<td>1993</td>
<td>Honkong, China</td>
<td>36–65 mo</td>
<td>Population-based</td>
<td>570</td>
<td>≥0.5</td>
<td>38.60%</td>
<td>WTR</td>
</tr>
<tr>
<td>Zhan et al.</td>
<td>2000</td>
<td>Xiamen, China</td>
<td>6–7 y</td>
<td>Population-based</td>
<td>Xiamen: 142</td>
<td>Xiamen</td>
<td>Xiamen</td>
<td>WTR</td>
</tr>
<tr>
<td>Zhao et al.</td>
<td>2000</td>
<td>Shunyi District, China</td>
<td>5–15 y</td>
<td>Population-based</td>
<td>5878</td>
<td>≥0.75</td>
<td>13.50%</td>
<td>WTR</td>
</tr>
<tr>
<td>Fan et al.</td>
<td>2004</td>
<td>Hong Kong, China</td>
<td>3–6 y</td>
<td>Population-based</td>
<td>522</td>
<td>≥1</td>
<td>21.10%</td>
<td>WTR</td>
</tr>
<tr>
<td>He et al.</td>
<td>2004</td>
<td>Guangzhou, China</td>
<td>5–15 y</td>
<td>Population-based</td>
<td>Retinoscopy: 4347</td>
<td>≥0.75</td>
<td>Retinoscopy: 21.4%</td>
<td>WTR</td>
</tr>
<tr>
<td>Dirani et al.</td>
<td>2010</td>
<td>Singapore</td>
<td>6–72 mo</td>
<td>Population-based</td>
<td>2639</td>
<td>≥1.5</td>
<td>8.40%</td>
<td>WTR</td>
</tr>
<tr>
<td>Li et al.</td>
<td>2014</td>
<td>Heilongjiang, China</td>
<td>5–9 y</td>
<td>Population-based</td>
<td>436</td>
<td>≥0.75</td>
<td>2.50%</td>
<td>WTR</td>
</tr>
<tr>
<td>Wu et al.</td>
<td>2013</td>
<td>Weihai, China</td>
<td>4–5 y</td>
<td>Population-based</td>
<td>476</td>
<td>≥0.75</td>
<td>31.00%</td>
<td>WTR</td>
</tr>
<tr>
<td>Lan et al.</td>
<td>2013</td>
<td>Guangzhou, China</td>
<td>4–9 y</td>
<td>Population-based</td>
<td>1663</td>
<td>≥0.75</td>
<td>8.10%</td>
<td>WTR</td>
</tr>
<tr>
<td>Current study</td>
<td></td>
<td>Nanjing, China</td>
<td>48–60 mo</td>
<td>Population-based</td>
<td>1817</td>
<td>≥0.5, ≥0.75, ≥1</td>
<td>38.4%, 23.3%, 14.2%, 6.3%</td>
<td>WTR</td>
</tr>
</tbody>
</table>

**Compensatory Role of Internal Astigmatism**

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A recent review suggests that intensive near work activities and limited outdoors time are major risk factors of myopia and the localization of the epidemic difference is considered to be due to the different educational pressures and outdoors time. Studies have shown that children with myopia were more likely to have astigmatism than children without spherical refractive error. The association between astigmatism and myopia prevalence might be a possible reason for the localization of the astigmatism epidemic. WTR was predominant in TA in most studies in Chinese children.

The prevalence and the distribution characteristics of CA were previously studied mainly among cataract patients and healthy adults. Few studies have studied the CA among young children and less fewer were population-based. Compared with the CA prevalence rate (38%) in Australian children and (29%) in Northern Ireland children, the prevalence of CA (≥ 1 D) in current study was higher (56%), likely attributed to ethnic differences. Consistent with the two previous studies, this study showed that WTR was the primary type of CA. Studies suggest that CA orientation may change with age, and WTR, common in young children, gradually shifts to ATR and OBL as age increases.

IA has been attributed to the refracting power of the lens, posterior cornea, and errors in optical centration. Some studies have concluded that CA exceeds TA by 0.5 D on average and that no internal compensation for CA exists. This conclusion was contradicted with other studies. Various methods were used to demonstrate the compensatory relationship between internal and corneal astigmatism. Kelly et al. found a significant negative correlation between internal and corneal astigmatism (ρ = −0.52, P = 0.005). However, this study only included 30 adult subjects and the vectorial feature of astigmatism was not completely considered into the analysis. Sayed obtained similar results (ρ = −0.32, P < 0.001) among 307 infants and young children; however, cylinder power was analyzed without vectorial decomposition. Figures were drawn by Huynh et al. to demonstrate the compensation of the magnitude, J₀ and J₄5, but their quantitative demonstration was inadequate. In our study, we first demonstrated that ACA exceeds TA in 1702 (93.7%) children with median difference of 0.88 D. Second, we demonstrated strong negative correlation between anterior corneal and internal J₀ (ρ = −0.74, P < 0.001), as well as anterior corneal and internal J₄5 (ρ = −0.87, P < 0.001). Third, we used the CF and found that internal J₀ compensated for total J₀ in varying degrees in 91.5% cases, and in 77.2% cases for J₄5. These data strongly suggest the substantial compensatory role of IA in reducing CA. Park et al. analyzed the compensation of IA among 356 myopic eyes from 178 adults (aged 19–65 years) based on CF. They found that in J₀, 4% was full compensation, 68% was undercompensation, and 8% was overcompensation. In J₄5, 12% was full compensation, 35% was undercompensation, and 12% was overcompensation. Their percentages of compensation (80% in J₀ and 50% in J₄5) were lower than that of our study both in J₀ and J₄5 components, particularly in the full compensation. In a similar study, 15% in J₀ and 50% in J₄5 components were less than that of our study both in J₀ and J₄5, respectively.

The strengths of the present study include its population-based design, large sample size, and standardized examination protocols performed by a trained team of two optometrists and two ophthalmologists. This study is limited in the less comprehensive collection of risk factors and the use of refraction data under noncycloplegic condition. However, one of the purposes of this study was to determine the role of IA under daily compensation status. The IA compensation after cycloplegia should be studied in the future. The simulated formula to calculate CA was used in this study. In the future, examination of posterior corneal astigmatism should be considered to derive accurate CA.

In summary, in the population aged 48- to 60-month-old children in the Yuhuatai District, the prevalence of TA was similar to that found in most previous studies among Chinese young children in cities and higher than that found in rural area. The CA prevalence was higher compared with limited studies in other countries. WTR was dominant in TA and CA, whereas ATR was most common in RA. By quantifying CE we demonstrated the compensatory role of IA in reducing CA, and this role was predominant in preschool children. Finally, the
larger AL/CR was significantly associated with higher risk of RA.

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