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 1.375. 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-10; 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 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 with the cylindrical axis equal to the flattest meridian. The anterior corneal surface power was calculated by 

\[ f_r = \frac{1}{r} \]

where \( r \) is the anterior curvature of the central radius and 1.376 is the refractive index of the cornea. Corneal refractive error was calculated by 

\[ C = \frac{1}{\cos(2A)} \]

where \( A \) is the axis of RA, and \( C_r \) is the magnitude of RA. The denominator in the above formulas 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.

\[ \frac{J_0}{C_0} = \frac{J_{180} - J_{15}}{J_{15}} \]

where \( J_0, J_{180}, J_{15} \) are \( J_0 \) of RA, TA, and CA, respectively; \( J_{180}, J_{15}, J_{15} \) are \( J_{15} \) of RA, TA, and CA, respectively; \( A_r \) is the axis of RA, and \( C_r \) is the magnitude of RA. 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.

\[ J_{180} = \frac{f_{180}}{f_{15}} \]

\[ J_{15} = \frac{f_{15}}{f_{15}} \]

where \( f_{180}, f_{15}, f_{15} \) are \( f_0 \) of IA and ACA, respectively; \( f_{180} \) and \( f_{15} \) are \( f_{15} \) 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.

\[ \frac{J_{180}}{J_{15}} \]

\[ \frac{J_{15}}{J_{15}} \]

The statistical package for the Social Sciences (V.13.0; 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 (\( p \)) was used to evaluate the relationships between magnitude of different types of astigmatism.
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 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>
<thead>
<tr>
<th>Table 1. Distribution and Constitution of Total Astigmatism, Corneal Astigmatism, and Residual Astigmatism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astigmatism</td>
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<tr>
<td></td>
</tr>
<tr>
<td>TA</td>
</tr>
<tr>
<td>≥0.5</td>
</tr>
<tr>
<td>≥1</td>
</tr>
<tr>
<td>≥1.5</td>
</tr>
<tr>
<td>CA</td>
</tr>
<tr>
<td>≥0.5</td>
</tr>
<tr>
<td>≥1</td>
</tr>
<tr>
<td>≥1.5</td>
</tr>
<tr>
<td>RA</td>
</tr>
<tr>
<td>≥0.5</td>
</tr>
<tr>
<td>≥1</td>
</tr>
<tr>
<td>≥1.5</td>
</tr>
</tbody>
</table>

FIGURE 1. Distribution of the magnitude of total, corneal, and internal astigmatism.
The denominator of CF was zero for anterior corneal $J_0$ in 40 children and for anterior corneal $J_{45}$ 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 ($J_{0}$ and $J_{45}$). 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 (5%), 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%, East Asian: 33.5%, 11.2%, 26.5%</td>
<td>Whole: OBL 39.1%, East Asian: WTR 49.6%</td>
</tr>
<tr>
<td>Harvey et al.</td>
<td>2010</td>
<td>Tohono O’odham, America</td>
<td>4–5 y</td>
<td>Population-based</td>
<td>211</td>
<td>≥2</td>
<td></td>
<td></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>African American: 548</td>
<td>≥1.5</td>
<td>African American: 8.0%, Hispanic: 11.6%</td>
<td>African American: 75%, Hispanic: 93.7%</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, Singapore</td>
<td>6–7 y</td>
<td>Population-based</td>
<td>Xiamen: 142</td>
<td>&gt;1</td>
<td>Xiamen City: 6.8%, Countryside: 8.7%, Singapore City: 17.1%</td>
<td>Xiamen, City WTR 88.9%, Countryside WTR=ATR, Singapore City: ATR 64%</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 (53%), ATR (7.9%), and oblique (39.1%)</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></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%, Autorefraction: 26.3%</td>
<td>WTR 80.5%</td>
</tr>
<tr>
<td>Dirani et al.</td>
<td>2010</td>
<td>Singapore</td>
<td>6–7 mo</td>
<td>Population-based</td>
<td>2639</td>
<td>≥1.5</td>
<td>8.30%</td>
<td></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></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 85.8%</td>
</tr>
<tr>
<td>Lan et al.</td>
<td>2013</td>
<td>Guangzhou, China</td>
<td>4–5 y</td>
<td>Population-based</td>
<td>1663</td>
<td>≥1.5</td>
<td>8.10%</td>
<td></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, ≥1.5</td>
<td>38.4%, 23.3%, 14.2%, 6.3%</td>
<td>WTR (64.0%, 70.0%, 75.2%, 87.7%)</td>
</tr>
</tbody>
</table>
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 with 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. 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 19–46 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, 206 Chinese myopic eyes of 206 Chinese children (6- to 16-years old), CF analysis revealed that compensation constituted 89.3% in J0 and 65.6% in J45, with 29.1% full compensation, 54.4% undercompensation, and 5.8% overcompensation in J0, and with 40.3% full compensation, 18.0% undercompensation, and 5.3% overcompensation in J45. The total compensation percentage was similar to that of the present study, but the constitution was different. The percentage of full compensation in our study was the highest. This difference may be attributed to age effect. The compensation weakens because of the shift of CA from WTR to ATR as age increases. The above two studies, as with our study, were carried out under noncycloplegic condition. In the study of 15,448 patients (median age of 74 years), the prevalence of CA (≥1 D) was 36.4%, which is lower than that of the present study. However, the prevalence of TA (≥1 D) was 32.0%, which is much higher. These results clearly demonstrated the attenuation of IA compensation in elderly people.

Genetic and environmental factors may play a role in the development of astigmatism. A meta-analysis of five Asian cohorts identifies PDGFRα on chromosome 4q12 as a susceptibility locus for corneal astigmatism. PDGFRα, a receptor for platelet-derived growth factor, is expressed in many retinal tissues in the eyes and is associated with ocular development. Interactions between the cornea and the eyelids, the extracocular muscles and the visual feedback dysfunction are the possible causes of astigmatism. However, no exact factor has been proved to lead to the development or progression of astigmatism. Ethnicity, age, myopia, hyperopia, maternal smoking during pregnancy, education level, ocular surgery, sex, accommodative convergence/accommodation (AC/A) ratio, and number of hours per day spent playing video games or on the computer were found to be associated with astigmatism. However, contradicting results exist in different studies. Spherical equivalent was the factor mostly studied. Researches have reported that for children, whose refractive refraction is difficult to perform, AL/CR may be the second choice in predicting spherical equivalent. In this study, all children received noncycloplegic refraction. There may be bias in refraction directly using noncycloplegic spherical refractive error due to accommodation, thus AL/CR was introduced. It is known that the higher is the AL/CR ratio the more myopic is the refraction. Generally, AL/CR has not been considered as a possible risk factor for astigmatism before. This study showed that AL/CR was not associated with TA or CA, but was associated with RA. This finding is interesting as the risk factors of RA has not been studied previously. Studies in the United States have found that children with myopia or hyperopia were more likely to have astigmatism than children without spherical refractive error. Interpreting the results of the present study on the association between AL/CR and spherical equivalent seems difficult, thus further studies are needed. The prevalence of TA was similar between sexes, which was consistent with the results from most previous studies. Association was found between age and TA, which should be verified in future studies.

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.

Acknowledgments

The authors thank the children, the corresponding parents or legal guardians, and all the members of the Maternal and Child Healthcare Hospital of Yuhua District, Nanjing, China, for helpful advice and support.

Supported by grants from the National Natural Science Foundation of China (Grant No. 81673198); the Natural Science Foundation of Jiangsu Province (Grant No. BK20161595); the Scientific Research Projects of Jiangsu Provincial Commission of Health and Family Planning (Grant No. H201507); and Jiangsu Province’s Key Provincial Talents Program (Grant No. QNRC2016563).

Disclosure: Z. Wang, None; D. Huang, None; X. Chen, None; H. Zhu, None; Q. Sun, None; Y. Wang, None; X. Zhang, None; Y. Wang, None; L. Zhai, None; C. Wang, None; H. Liu, None

References