The Associations of Lens Power With Age and Axial Length in Healthy Chinese Children and Adolescents Aged 6 to 18 Years

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Purpose. To investigate the relationship between lens power and age as well as the relationship between lens power and axial length (AL) in Chinese children and adolescents.

Methods. The participants underwent a comprehensive ophthalmic examination that included AL, cycloplegic refraction, and Pentacam measurements. The crystalline lens power was calculated using Bennett’s formula and then compared among the children of different age groups, refractive statuses, and AL categories. The association of lens power and AL was analyzed using multiple regression.

Results. A total of 1992 children and adolescents aged 6- to 18-years old were included. The difference in lens power was greater before 10-years old, followed by a relatively smaller difference in children aged 10 to 14 years and the difference in lens power came to a near plateau in adolescents after 14-years old. The negative association between lens power and AL was found to be more evident in nonmyopes than in myopes irrespective of age (younger than 10 years: nonmyopes: $\hat{\beta} = -1.499$, myopes: $\hat{\beta} = -0.872$; older than 10 years: nonmyopes: $\hat{\beta} = -1.288$, myopes: $\hat{\beta} = -0.590$, all $P < 0.001$).

Conclusions. The lens power in children and adolescents aged 6 to 18 years exhibited three stages. The association between lens power and AL differed between the nonmyopes and myopes. These findings suggested that less reduction in lens power might be associated with both growing age and increasing AL in myopes.

Keywords: lens power, myopia, refractive error

Lens power plays an important role in the determination of refractive status. Most children are born hyperopic. During the eye growth years, the losses of corneal and lens powers compensate for the axial elongation of the eye to keep refraction stable in a clustered distribution and gradually lead the refractive status toward emmetropia.1–3 The corneal power stabilizes in the first year or two after birth; in contrast, lens power usually changes throughout life.4 For school children and adolescents, the balance between axial length (AL), and lens power primarily determines refraction, and myopia develops if the rate of axial elongation outpaces the reduction in lens power.5,4,6

Lens power cannot be measured directly because it is inside the eye. Lens power can be obtained either by phakometry, which determines the radius of the curvature by analyzing Purkinje image data,7,8 or calculated from other ocular biometry and refraction parameters, for example, using Bennett’s formula, assuming that the lens is similar to that of the Gullstrand-Emsley model eye.9,10 These methods enable relatively accurate estimates of lens power in vivo, and thus, estimations of the characteristics of lens power from infancy to adulthood.2,4,11–15 According to previous studies, during the early childhood development period, the lens loses power from infancy to school age at a rapid rate that slowly but continually decreases from ages 10 to 14.14,15 In adulthood, the lens power exhibits a monotonous decrease with age with a steeper decline after age 50.5,14 However, the changes in lens power in adolescents aged 14 to 18 years have not yet been reported. Additionally, the relationship between the change in lens power and axial elongation is controversial. Lens power has been demonstrated to be lower in myopic children than in emmetropic children, which might be a compensatory effect for increased axial elongation.5,4,6,11 However, because the patterns of change in lens power with age appear to be similar across ethnic groups (white and Asian children),3,4,11 whose patterns of refractive error, specifically the prevalences of myopia are different,16–18 it seems that they represent a developmental change that is not regulated in relation to AL or refractive error.

To further elucidate these uncertain issues, we included a large sample of Chinese school children and adolescents aged 6 to 18 years with a wider range of refractive errors in this cross-sectional study. The crystalline lens power was calculated using...
were defined as SE less than or equal to −0.5 diopters (D), −0.5 D less than SE less than or equal to +0.5 D, and SE greater than +0.5 D, respectively.\textsuperscript{19,22} Myopia was further categorized into high myopia, moderate myopia, and mild myopia, which were defined as SE less than or equal to −5.0 D, −5.0 D less than SE less than or equal to −3.0 D, and −3.0 D less than SE less than or equal to −0.5 D, respectively.

The crystalline lens power ($P_L$) was calculated using Bennett’s formula,\textsuperscript{9,24} that is,

$$P_L = \frac{-1000n(Scv + K)}{1000n - (ACD + c_1T)(Scv + K)} + \frac{1000n}{c_2T + V}$$

in which $T$ is the lens thickness, $V$ is the vitreous depth, $n = 4/3$ of the aqueous and vitreous indices, $c_1 = 0.506$, and $c_2 = -0.358$ as estimated using the Gullstrand-Emsley eye model. The spherical equivalent refraction was defined as $Scv = SE/(1 - 0.014 \times SE)$. The effective $ACD$ included the central corneal thickness and the $ACD$ as given by the Pentacam. Accounting for the posterior corneal surface, the corneal power was calculated as follows (Manns E. IOVS 2014;55:ARVO E-Abstract 3785)\textsuperscript{25,26}:

$$K_{m,a} = \frac{(n_c - 1)}{R_{m,a}}$$

$$K_{m,p} = \frac{(n - n_c)}{R_{m,p}}$$

$$K = K_{m,a} + K_{m,p} - K_{m,a} \times K_{m,p} \times CCT/n_c$$

where $K_{m,a}$ and $K_{m,p}$ are the mean anterior and posterior keratometric measurements, respectively, $R_{m,a}$ and $R_{m,p}$ are the anterior and posterior corneal radii of curvature, respectively; $CCT$ is the central corneal thickness; and $n_c (= 1.376)$ is the corneal refractive index.

### Statistical Analyses

A database was created using Epidata 3.1 (EpiData Association, Odense, Denmark). All data were independently double entered by two trained staff members, and all discrepancies were adjudicated. The statistical analyses were conducted using IBM SPSS statistics version 24.0 (IBM Co., Armonk, NY, USA). Because the biometry data and refractive errors of the two eyes were strongly correlated (the Pearson’s correlation coefficients ranged from 0.843–0.973), only the data from the participants’ right eyes were included in the statistical analyses. The parameters were presented as the means ± SDs for the continuous variables and as the rates (proportions) for the categoric data. Intergroup differences were tested with Student’s $t$-tests (between sexes) or with ANOVA with post hoc tests (for the refractive groups and AL categories). Correlations of the ocular biometric parameters were analyzed with Pearson correlation coefficients. Multiple regression analysis was performed to explore the association between lens power and AL after adjusting for the other factors of nonmyopes and myopes both before and after 10-years old. Statistical significance was set at $P$ less than 0.05 (2-tailed).

### RESULTS

#### General Characteristics

Out of the 2883 children and adolescents who underwent the examination, 891 lacked data of lens thickness when captured by Pentacam, so 1992 (69.1%) children were included in final analysis. Participants included in the study had longer AL (23.67 ± 1.18 vs. 23.49 ± 1.18, $P < 0.001$), stronger corneal power (41.70 ± 1.35 vs. 41.45 ± 1.44, $P < 0.001$), and deeper
difference in children aged 10 to 14 years (mean difference of ~0.95 D); subsequently, the difference in lens power came to a near plateau in older childhood aged 14 to 18 (0.15 D difference; Table 2, Fig. 2). When stratified by sex, greater difference of lens power from 6 to 10 years was observed in both sexes (boys: 1.72 D; girls: 2.17 D). However, the boys exhibited smaller difference from 10 to 14 years (mean difference of 1.00 D) and a plateau from ages 14 to 18 years (mean difference of 0.20 D), whereas the girls exhibited a similar difference from ages 10 to 18 years (differences of 0.45 D from ages 10–14 years and 0.46 D from age 14–18 years, respectively; Table 2, Fig. 2). Figure 2 also indicates that the girls exhibited greater lens powers across all age groups (all \( P < 0.001 \)).

### Influence of Refraction

There was a positive correlation between lens power and SE (\( r = 0.332, \ P < 0.001 \)). The polynomial curve showed that the positive correlation only existed when SE greater than \(-5.00 \) D, while a negative correlation was observed when SE less than \(-5.00 \) D (Fig. 5A). \ The distributions of lens power across the different refractive statuses were further investigated with ANOVA. The results revealed a significant difference between the refraction groups (\( P < 0.001 \)) in which the values in the hyperopes were markedly greater on average than those of the emmetropes, which were greater than those in the mild myopes (\( P < 0.001 \); Table 3). However, there were no significant differences between the mild and moderate myopes or between the moderate and high myopes (\( P = 0.687 \) for the moderate versus mild myopes and \( P = 0.124 \) for the high versus moderate myopes; Table 3). Similar pattern of differences was observed in the boys and girls (all \( P < 0.001 \); Table 3).

### Association with AL

There was a negative correlation between lens power and AL (\( r = -0.666, \ P < 0.001 \)). The polynomial curve showed that the negative correlation was observed only when AL was less than 25 mm, while there was no significant association between lens power and AL when AL was greater than 25 mm (Fig. 3B). When the eyes were divided into 1-mm bins according to AL, an ANOVA also demonstrated a negative correlation between lens power and AL, and the difference in lens power was greater in the shorter eyes (AL \(< 24–25 \) mm) while smaller in the longer eyes (AL \(> 25 \) mm, Table 4). A similar pattern of differences was observed in the boys and girls (all \( P < 0.001 \); Table 4). A significant difference in lens thickness was observed in the shorter eyes (AL \(\leq 24–25 \) mm), and the differences decreased in the longer eyes (AL \(< 22 \) mm: 3.56 ± 0.17 mm; AL 22–25 mm: 3.49 ± 0.16 mm; AL 23–24 mm: 3.42 ± 0.15 mm; AL 24–25 mm: 3.37 ± 0.14 mm; AL 25–26 mm: 3.35 ± 0.15 mm; and AL \(> 26 \) mm: 3.32 ± 0.17 mm).

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**Table 1.** General Characteristics of the 1992 Participants and Comparison Between Boys and Girls

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Total, ( N = 1992 )</th>
<th>Boys, ( N = 1037 )</th>
<th>Girls, ( N = 955 )</th>
<th>( P ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>10.2 ± 3.1</td>
<td>10.2 ± 3.1</td>
<td>10.2 ± 3.1</td>
<td>0.949*</td>
</tr>
<tr>
<td>Lens power, D</td>
<td>25.28 ± 1.93</td>
<td>24.76 ± 1.87</td>
<td>25.84 ± 1.83</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Lens thickness, mm</td>
<td>3.42 ± 0.17</td>
<td>3.41 ± 0.17</td>
<td>3.44 ± 0.16</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>Corneal power, D</td>
<td>41.70 ± 1.33</td>
<td>41.37 ± 1.26</td>
<td>42.05 ± 1.32</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>ACD, mm</td>
<td>3.22 ± 0.23</td>
<td>3.27 ± 0.23</td>
<td>3.18 ± 0.22</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>AL, mm</td>
<td>23.67 ± 1.18</td>
<td>23.91 ± 1.15</td>
<td>23.42 ± 1.17</td>
<td>&lt;0.001*</td>
</tr>
<tr>
<td>SE, D</td>
<td>−0.39 ± 2.08</td>
<td>−0.34 ± 2.02</td>
<td>−0.44 ± 2.16</td>
<td>0.298*</td>
</tr>
</tbody>
</table>

* Statistical significance was tested using Student's \( t \)-test.

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**Figure 1.** The distribution of lens power for the total population (age range, 6–18 years).
After adjusting for age, sex, and lens thickness, lens power was found to be negatively associated with AL. This association was more evident in nonmyopes than in myopes both before and after age 10 (nonmyopes younger than 10 years: $\beta = -1.499$; myopes younger than 10 years: $\beta = -0.872$; nonmyopes older than 10 years: $\beta = -1.288$; and myopes older than 10 years: $\beta = -0.390$; all $P < 0.001$, Table 5). In nonmyopes, the listed factors explained more compared with those in myopes ($R^2$: nonmyopes younger than 10 years: 0.815; myopes younger than 10 years: 0.664; nonmyopes older than 10 years: 0.844; myopes older than 10 years: 0.635, Table 5).

**DISCUSSION**

To our knowledge, the present study is the first to investigate the characteristic of lens power and the factors that associate this characteristic in children and adolescents aged 6 to 18 years in a single population with a wide refraction range (–11.38 to 9.13 D). The results revealed that there was a greater difference in lens power in early childhood over the age of 6 to 10 years, followed by a relatively smaller difference in children aged 10 to 14 years, while the difference in lens power came to a near plateau in older childhood aged 14 to 18. Additionally, the results implied that lens power differences were also associated with AL. More evident associations of lens power with AL were observed in the nonmyopes than in the myopes irrespective of age and sex.

Bennett’s formula was used to calculate lens power in the present study. This formula is widely used and allows for the accurate calculation of the lens power without the use of commercially unavailable devices.\textsuperscript{10,24} To account for the influence of the posterior cornea on the lens power calculation, the total corneal power was calculated from the anterior and posterior radii using a refractive index of 1.376.\textsuperscript{14,26} The calculated lens powers were in relatively close agreement with the values obtained by Iribarren\textsuperscript{4} (mean lens power of boys: 24.22 D, mean lens power of girls: 25.39 D),

<table>
<thead>
<tr>
<th>Age, y</th>
<th>N (% of boys)</th>
<th>Total</th>
<th>Boys</th>
<th>Girls</th>
<th>P Value</th>
<th>SE, D</th>
<th>AL, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>70 (51.4)</td>
<td>26.97 ± 1.97</td>
<td>26.31 ± 1.85</td>
<td>27.68 ± 1.88</td>
<td>0.003*</td>
<td>1.06 ± 0.84</td>
<td>22.61 ± 0.74</td>
</tr>
<tr>
<td>7</td>
<td>294 (52.4)</td>
<td>26.34 ± 1.76</td>
<td>25.92 ± 1.76</td>
<td>26.80 ± 1.65</td>
<td>&lt;0.001*</td>
<td>1.05 ± 1.17</td>
<td>22.87 ± 0.75</td>
</tr>
<tr>
<td>8</td>
<td>278 (51.4)</td>
<td>26.04 ± 1.76</td>
<td>25.57 ± 1.60</td>
<td>26.74 ± 1.66</td>
<td>&lt;0.001*</td>
<td>0.50 ± 1.08</td>
<td>23.16 ± 0.85</td>
</tr>
<tr>
<td>9</td>
<td>298 (53.0)</td>
<td>25.35 ± 1.75</td>
<td>24.86 ± 1.54</td>
<td>25.90 ± 1.82</td>
<td>&lt;0.001*</td>
<td>−0.01 ± 1.62</td>
<td>23.50 ± 0.96</td>
</tr>
<tr>
<td>10</td>
<td>359 (51.0)</td>
<td>25.04 ± 1.68</td>
<td>24.59 ± 1.76</td>
<td>25.51 ± 1.47</td>
<td>&lt;0.001*</td>
<td>−0.31 ± 1.50</td>
<td>23.63 ± 0.86</td>
</tr>
<tr>
<td>11</td>
<td>250 (51.6)</td>
<td>24.85 ± 1.80</td>
<td>24.40 ± 1.77</td>
<td>25.30 ± 1.71</td>
<td>&lt;0.001*</td>
<td>−0.82 ± 1.84</td>
<td>23.98 ± 1.09</td>
</tr>
<tr>
<td>12</td>
<td>80 (56.3)</td>
<td>24.69 ± 1.52</td>
<td>24.25 ± 1.40</td>
<td>25.26 ± 1.49</td>
<td>0.003*</td>
<td>−0.45 ± 1.84</td>
<td>23.90 ± 0.71</td>
</tr>
<tr>
<td>13</td>
<td>62 (51.6)</td>
<td>24.50 ± 1.52</td>
<td>24.05 ± 1.50</td>
<td>24.98 ± 1.42</td>
<td>0.016*</td>
<td>−0.89 ± 1.99</td>
<td>23.98 ± 1.05</td>
</tr>
<tr>
<td>14</td>
<td>41 (65.9)</td>
<td>24.09 ± 1.63</td>
<td>23.59 ± 1.51</td>
<td>25.06 ± 1.45</td>
<td>0.005*</td>
<td>−1.15 ± 1.83</td>
<td>24.23 ± 1.02</td>
</tr>
<tr>
<td>15</td>
<td>34 (35.3)</td>
<td>24.30 ± 1.50</td>
<td>23.59 ± 1.34</td>
<td>24.69 ± 1.47</td>
<td>0.040*</td>
<td>−2.29 ± 2.55</td>
<td>24.59 ± 1.19</td>
</tr>
<tr>
<td>16</td>
<td>81 (50.6)</td>
<td>24.12 ± 2.21</td>
<td>23.30 ± 1.96</td>
<td>24.95 ± 2.17</td>
<td>0.001*</td>
<td>−3.05 ± 2.35</td>
<td>25.11 ± 1.19</td>
</tr>
<tr>
<td>17</td>
<td>75 (52)</td>
<td>23.94 ± 1.69</td>
<td>23.52 ± 1.74</td>
<td>24.62 ± 1.36</td>
<td>0.001*</td>
<td>−3.06 ± 2.56</td>
<td>25.11 ± 1.33</td>
</tr>
<tr>
<td>18</td>
<td>70 (54.3)</td>
<td>23.94 ± 1.83</td>
<td>23.59 ± 1.85</td>
<td>24.60 ± 1.59</td>
<td>0.005*</td>
<td>−4.02 ± 2.40</td>
<td>25.50 ± 1.20</td>
</tr>
</tbody>
</table>

* Statistical significance was tested using Student’s t-test.

![Figure 2](http://arvojournals.org/)  
**Figure 2.** The mean lens power stratified by age for both sexes.

![Figure 3](http://arvojournals.org/)  
**Figure 3.** (A) Relationship between SE and lens power (polynomial fitting). (B) Relationship between AL and lens power (polynomial fitting).
who calculated corneal power from the anterior corneal radius using a refractive index of 1.3515, but found to be greater than that of another study that used the anterior corneal radius and a refractive index of 1.328 (lens power of 23.08 D on average). This difference might be due to the older age (around 14 years old) and higher prevalence of myopia (mean SE of −2.10 D) used in the latter (Li et al. 15) sample.

We found that the lens power in children and adolescents aged 6 to 18 years exhibited three stages. During early childhood (ages 6–10 years), the pattern of difference in lens power appeared to be greater (a mean difference of −1.93 D). After the age of 10 years, lens power difference was relatively smaller (mean reduction of 0.95 D). These phenomena were consistent with those found in previous studies. However, because most previous studies only investigated changes and/or differences in lens power to the age of 14 years, the lens power changes and/or differences from 14 to 18 years remain unknown. The data from the current study indicated that difference in lens power came to a near plateau during this period (decrease of only 0.15 D). This reduction rate was consistent with those found in previous studies. However, because most previous studies only investigated changes and/or differences in lens power to the age of 14 years, the lens power changes and/or differences from 14 to 18 years remain unknown. The data from the current study indicated that difference in lens power came to a near plateau during this period (decrease of only 0.15 D). This reduction rate was similar to that in adults aged 20- to 50-year-olds who exhibited a monotonous decrease in lens power of approximately 0.37 to 0.12 D every 5 years. Both the flattening of lens curvature as the lens is thinned and the decline in internal power as the gradient is compacted are responsible for lens power loss in growing children. After 10 years, especially after 14 years of age (as observed in our study), and until the age of 50, the axial thickness increases with age at a greater rate than the equatorial diameter. Meanwhile, the gradient index profile gradually resembles a relatively maximal climbing profile until the adult index plateau is developed. Together, these factors contribute to the slowing of lens power loss.

The relationships between AL and lens power across different refractive statuses remain controversial, especially around the onset of myopia. Previous longitudinal studies have indicated similar rates of reduction in lens power in myopes and nonmyopes, although an increased rate of lens power loss has been observed at the onset of myopia. However, the results of the current study indicated that lens power exhibited a stronger association with AL in nonmyopes but a relatively weaker association in myopes. These results were consistent with those of a longitudinal study by Mutti et al., who observed a stop in power loss after the onset of myopia, and those of a cross-sectional study of 14-year-old Chinese children conducted by Li et al., who found a similar pattern of change in girls but not in boys. Because the crystalline lens also undergoes a reduced rate of power loss after the age of 10, the finding of changes in lens power in myopes and longer eyes could be an age effect because more myopic and longer eyes are usually found in older children. However, our results further revealed a more evident association of lens power with AL in nonmyopes than in myopes after adjusting for age (split at the age of 10), sex, and lens thickness, which indicated that the compensatory ability of lens power became smaller not only with increasing age for its natural development but also in myopes as axial elongating.

There might be some internal mechanisms, which can explain the difference in lens power changes between myopes and nonmyopes. Before the onset of myopia, lens power reduces in the compensation of AL elongation to maintain emmetropia, which is a co-effect of changes in both the shape and the gradient refractive index of the lens. However, lens power loss might be limited when the shape of the gradient refractive index profile approaches a relatively maximal rate of increase. In contrast, axial growth, which is mainly regulated by environmental factors, such as time spent outdoors during the school years, might have no endpoint. Myopia develops when the rate of axial growth outpaces the compensatory loss of lens power. After the onset of myopia, as the eye elongates to a critical point, the compensatory ability of the crystalline lens might be further influenced by mechanisms that include restricted equatorial growth caused by abnormally thicker and longer ciliary muscles in myopes. The smaller differences in lens thickness among those with longer ALs might provide support to the above speculation. Future investigations that include more myopes, particularly high myopes, and longitudinal studies will be necessary to fully understand the complex interactions between lens power and myopia.
### Table 5. Multivariate Regression Analysis of Associations With Lens Power for Nonmyopes and Myopes Before and After the Age of 10

<table>
<thead>
<tr>
<th>Variables</th>
<th>Nonmyopes, N = 921</th>
<th>Myopes, N = 236</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>Estimate, 95% CI</td>
<td>Estimate, 95% CI</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>0.065 (0.120 to 0.000)</td>
<td>-0.134 (0.202 to 0.035)</td>
<td>0.009</td>
</tr>
<tr>
<td>Sex, boys vs. girls, D</td>
<td>0.094 (0.058 to 0.131)</td>
<td>-0.095 (0.125 to -0.035)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>AL, mm</td>
<td>0.035 (0.014 to 0.056)</td>
<td>0.030 (0.019 to 0.041)</td>
<td>0.001</td>
</tr>
<tr>
<td>Lens thickness, D/mm</td>
<td>3.577 (3.418 to 3.736)</td>
<td>4.676 (4.632 to 4.720)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Adjusted for all variables listed, R² for nonmyopes younger than 10y: 0.065, R² for myopes younger than 10y: 0.005, R² for myopes older than 10y: 0.033.

There are several limitations in our study. First, there were fewer participants aged 14 to 18 years (accounting for only 15.1% of the total sample) than participants in the other age groups. However, the pattern of lens power change in the 14- to 18-year-old group was clear. Future studies that include more adolescents are needed to confirm our findings. Additionally, the number of participants with high myopia was less than those in the other refractive groups. Our results demonstrated a relatively greater lens power among the high myopes than among the moderate myopes, although this difference was not statistically significant. This lack of significance might be due to the lower number of high myopes who were enrolled in the current study. Finally, this was a cross-sectional study, and thus, the causal effects of the associations we observed (especially regarding the relationship between lens power and AL) cannot be determined. We have performed a follow-up investigation of this population; the longitudinal data are being analyzed, and the results will be presented in the future.

In conclusion, the results of the current study demonstrated an even slower reduction in lens power after the age of 14 years in adolescents, and this finding fills gaps in this field. Additionally, these results imply that refraction and AL also influenced the rate of lens power loss, and these effects were possibly due to the restricted equatorial growth of the eye.

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### References

The Relationship Between Lens Power and Age, AL