Comparison of Ocular Component Growth Curves among Refractive Error Groups in Children

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PURPOSE. To compare ocular component growth curves among four refractive error groups in children.

METHODS. Cycloplegic refractive error was categorized into four groups: persistent emmetropia between −0.25 and +1.00 D (exclusive) in both the vertical and horizontal meridians on all study visits (n = 194); myopia of at least −0.75 D in both meridians on at least one visit (n = 247); persistent hyperopia of at least +1.00 D in both meridians on all visits (n = 43); and emmetropizing hyperopes of at least +1.00 D in both meridians on at least the first but not at all visits (n = 253). Subjects were seen for three visits or more between the ages of 6 and 14 years. Growth curves were modeled for the persistent emmetropes to describe the relation between age and the ocular components and were applied to the other three refractive error groups to determine significant differences.

RESULTS. At baseline, eyes of myopes and persistent emmetropes differed in vitreous chamber depth, anterior chamber depth, axial length, and corneal power and produced growth curves that showed differences in the same ocular components. Persistent hyperopes were significantly different from persistent emmetropes in most components at baseline, whereas growth curve shapes were not significantly different, with the exception of anterior chamber depth (slower growth in persistent hyperopes compared with emmetropes) and axial length (lesser annual growth per year in persistent hyperopes compared with emmetropes). The growth curve shape for corneal power was different between the emmetropizing hyperopes and persistent emmetropes (increasing corneal power compared with decreasing power in emmetropes).

CONCLUSIONS. Comparisons of growth curves between persistent emmetropes and three other refractive error groups showed that there are many similarities in the growth patterns for both the emmetropizing and persistent hyperopes, whereas the differences in growth lie mainly between the emmetropes and myopes. (Invest Ophthalmol Vis Sci. 2005;46:2317–2327) DOI:10.1167/iovs.04-0945
were +1.50 D or more hyperopic at age 5 or 6 years (n = 33) and 88% of children who were between +1.25 and +1.49 D at age 5 or 6 (n = 8) years remained hyperopic at age 13 or 14 years. These studies indicate that children with hyperopia are more likely to remain hyperopic. Ocular components have not been examined in hyperopes over time.

The studies evaluating refractive error over time have addressed some of the components that change as refractive error changes, with particular attention to the increase in axial length and vitreous chamber depth and the progression of myopia. The purpose of this study was to generate and compare the growth curves for the ocular components in school-aged emmetropes, myopes, and hyperopes that are emmetropizing and those with persistent hyperopia. Understanding how growth of the various components of the eye in detail may help to explain the different behavior of refractive errors as a function of age: how myopes progress, how emmetropes remain stable, why some hyperopes emmetropize, and why others remain hyperopic. The results of this analysis expand on the current literature by including measures of crystalline lens shape and power in addition to corneal power and axial dimensions.

Methods

Subjects for these analyses were participants in the Orinda Longitudinal Study of Myopia (OLSM). Children were recruited from the Orinda Union School District in California to participate in a longitudinal study evaluating risk factors for myopia and the development of the associated ocular components. Individuals and their parents provided informed consent according to the tenets of the Declaration of Helsinki. Informed consent procedures and the study protocol were approved by the University of California, Berkeley’s Committee for the Protection of Human Subjects. Data presented herein were obtained from 1989 through 2001. To be included in these analyses, the subject had to have at least three visits between the ages of 6 to 14 years to allow for the generation of ocular component growth curves.

The ocular components of the right eye only were measured. Corneal anesthesia was used twice: once to minimize the discomfort from the cycloplegic drops and later to allow ultrasonography. One drop of 0.5% proparacaine was followed by two drops of 1% tropicamide, 5 minutes apart, for cycloplegia. Measurements were made 25 minutes after the initial instillation. Cycloplegic refractive error was measured by autorefraction with an open-view infrared autorefractor (model R-1; Canon USA, Lake Success, NY; no longer manufactured).

The left eye was occluded with an eye patch during autorefraction. The autorefractor was set up so that the free viewing space was measured by autorefraction with an open-view infrared autorefractor (model R-1; Canon USA, Lake Success, NY; no longer manufactured).

The 10 spherocylindrical refractions were averaged by using the matrix method described by Harris. This method treats each spherocylinder as a vector that can then be manipulated by standard linear algebra matrices to provide means and standard deviations of sphere, cylinder, and axis. Mean spherocylinders were also converted to horizontal and vertical meridian refractions.

Corneal power in the vertical meridian was measured with photokeratography (KERA 9-ring CorneaScope [Kera Corp., Santa Clara, CA] from 1989 to 1990 and 1990 to 1991). One photograph was taken on each occasion. The photograph was analyzed on a proprietary, video-based, computer-assisted analysis system (KERA-Scan; Kera Corp.). From 1991 to 1992 on, the topographic modeling system was used. The third inferior ring (corresponding to a location roughly 1.5 mm from the center) in the vertical meridian was selected for this analysis, primarily because it was a reading free of contamination from lid position and therefore obtainable in every child.

Crystalline lens radii of curvature were obtained with video phakometry, which is an updated version of stillflash photography comparison ophthalmophakometry that measures Purkinje images I, III, and IV formed close to the optic axis by a collimated light source, with digitized, computer analysis of multiple images. The child was seated behind the instrument with an eye patch on his or her left eye and instructed to fixate a red-light-emitting diode on a movable arm while the reflected Purkinje images I, III, and IV were recorded. Lens power was calculated with the Gullstrand-Emmet schematic eye indices of refraction for the aqueous and the vitreous (4/5) and the crystalline lens (1.410). An equivalent index and calculated lens power were also found with an iterative procedure that produces agreement between measured refractive error and that calculates by using ocular component data from ultrasound and Purkinje image data from phakometry.

Anterior chamber depth, lens thickness, and vitreous chamber depth (average of five readings for each) were measured through the dilated pupil with the A-scan ultrasound unit (model 820; Allergan-Humphrey, Carl Zeiss Meditec, Dublin, CA), with a handheld probe on a semiautomatic measurement mode with a drop of 0.5% proparacaine instilled in the right eye. Readings in which the retinal peak was marked at other than its anterior-most point were discarded, either online or after all five readings had been obtained.

The data entry and verification for 1989 through 1995 were conducted by the Data Management Unit of the Survey Research Center at the University of California at Berkeley. Data from 1996 through 2001 were entered and verified at the Optometry Coordinating Center at The Ohio State University. All data were double-entered into databases specifically designed for the study.

Children included in these analyses met the following criteria: Each child attended at least three study visits between the ages of 6 and 14 years. A child was defined as a myope if both the horizontal and vertical meridians of the right eye under cycloplegia were −0.75 D or more myopic at one or more visits. A child was defined as a persistent hyperope if both the horizontal and vertical meridians were at least +1.00 D or more hyperopic at all visits. Emmetropes were defined as being between −0.25 and +1.00 D (exclusive) in both meridians at all study visits. Children who began as hyperopes (horizontal and vertical meridians at least +1.00 D) at the first visit but did not demonstrate at least +1.00 D of hyperopia at all study visits were considered to be emmetropizing hyperopes. Children not fitting one of these four criteria were not included in the analysis.

Statistical Methods

Descriptive statistics (means and frequencies) were calculated for age and for each of the ocular components at the child’s first examination. Growth curves were generated relating age and each ocular component: lens equivalent index, calculated equivalent lens power, Gullstrand lens power, lens thickness, anterior chamber depth, axial length, vitreous chamber depth, and corneal power. The curves were generated in mixed models run on computer (SAS ver. 9.1; SAS Institute Inc., Cary, NC). This method allows for multiple points to be used to generate each subject’s curve and then creates an “average” model that incorporates the individual curves into an average curve, according to the maximum likelihood. The model also allows for specification...
of the structure of the variance–covariance matrix to describe the
relation between the correlated longitudinal observations. Variance–
covariance matrices investigated were the unstructured and com-
pound symmetry matrices. Model parameters were determined by
maximum-likelihood methods.24 Mixed modeling is particularly pow-
erful because it allows for the presence of a variable number of data
points—that is, an otherwise eligible subject is not excluded for miss-
ing observations due to the potential for differing lengths of follow-up.
Missing data are handled within the iterative maximum-likelihood pro-
cedure, in which all available subject data were used, even in the
calculations. The maximum-likelihood procedure chooses the param-
eters that will maximize the likelihood of observing the given set of
sample data.

Growth curves were initially modeled for each component, includ-
ing only the data from emmetropic children.25 In short, each outcome
was modeled as a linear function of several mathematical forms of age,
which included natural log, quadratic, age,2 inverse(age), and in-
verse[natural log(age)] and assuming points of inflection. In these latter
models, cut points based on age were included in the model to allow
the shape of the curve to vary before and after a given cut point. The
cut points were selected within 0.5-year increments from age 9 to 12
years, so that there was a sufficient number of data points both before
and after the cut point and so that the cut point was within the age at
which myopia might be expected to develop. Akaike's information
criterion (AIC) values from each model were used to determine which
function of age and which variance–covariance structure best de-
scribed the ocular component changes.26 The best model was consid-
ered to be the one with the lowest AIC value, and model effectiveness
was assessed by the model

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The probability was used to assess the
significance of model fit. Once the best-fitting model for emmetropes
was determined, this functional form was applied to the data for the
myopes and for both groups of hyperopes, to derive curves for those
groups. Parameter estimates from each curve were then compared
with corresponding parameters from the emmetropic model. Allowing
each refractive group to have growth curves with their best-fitting
functional form would prevent comparisons between curves because
of the lack of a comparison method across models. By fixing the
functional form as the optimal model for the emmetropes, we main-
tained the ability to compare the estimated curves among refractive
error groups.

RESULTS

Two hundred forty-seven children were classified as myopic.
Of these, 76.1% were nonmyopic at baseline. There were 43
persistent hyperopes, 253 emmetropizing hyperopes, and 194 persistent emmetropes. Eight children who were emmetropic at baseline became myopes during the course of the study. Figure 1 presents the children available for analysis and the reasons for exclusion. Males were 44.1%, 46.5%, 56.7%, and 46.5% of the myopes, persistent hyperopes, persistent emmetropes, and emmetropizing hyperopes, respectively. Racial-ethnic group was reported by a parent. Overall, whites accounted for the majority of the sample (85.0%), with 0.4% African American, 11.1% Asian, 2.0% Hispanic, 0.3% American Indian and 1.1% “other” racial-ethnic group. The percentage of children classified into each refractive error group by race or ethnic group is shown in Table 1.

The number of visits per subject differed significantly among refractive error groups (Table 2, $\chi^2 = 139.96, P < 0.0001$), with the persistent emmetropes more likely to have attended fewer visits than the myopes, the persistent hyperopes, or the hyperopes. Thirty-seven percent of the myopes, 42% of the emmetropizing hyperopes, and 53% of the persistent hyperopes had a full eight visits. Only 15% of the persistent emmetropes attended all eight visits. Mean years of follow-up (±SD) were 3.7 ± 1.9 for the persistent emmetropes, 5.0 ± 2.0 for the myopes, 5.4 ± 1.7 for the emmetropizing hyperopes, and 4.6 ± 2.1 years for the persistent hyperopes (analysis of variance, $P < 0.0001$). Post hoc comparisons show that the persistent emmetropes had a significantly shorter follow-up period than did the myopes ($P = 0.0023$), the emmetropizing hyperopes ($P < 0.0001$), and the persistent hyperopes ($P < 0.0001$). There was also a marginally significant difference between the follow-up period of emmetropizing hyperopes and persistent hyperopes ($P = 0.046$). The visits for all subjects were overwhelmingly consecutive—that in, a subject who had three visits had three consecutive visits over a 2-year period, not visits spaced out over many years.

Baseline mean age and ocular component data for each of the refractive groups are presented in Table 3. Because of the differences in age between persistent emmetropes and the other refractive error groups at baseline, comparisons of all components were adjusted for age. Persistent emmetropes changed, on average, $-0.19 ± 0.24$ D from their first to their last visit. We saw very few emmetropic subjects with shifts within the category. For example, of the subjects who started at the higher end of emmetropia (≥ ±0.75 D both meridians), only 5% fell below 0 D on the last visit. This helps demonstrate the stability of refractive error in the emmetropic group. The myopes were evaluated to see whether there was evidence of a group of stable myopes to compare to myopes who could be identified as progressing myopes. Of the myopes, only 16 (6.5%) progressed 0.25 D or less over their visits. As a yearly average, 86% of the subjects showed an average yearly change of more than 0.25 D. Based on these data, there does not seem to be strong evidence of a group of stable myopes among our subjects.

At baseline, persistent emmetropes and myopes differed in axial length, vitreous chamber depth, and corneal power after adjustment for age. Persistent emmetropes differed from the emmetropizing hyperopes in anterior chamber depth and axial length and from the persistent hyperopes in lens refractive index, calculated lens power, anterior chamber depth, axial length, and vitreous chamber depth. Persistent emmetropes had a significantly longer axial length, longer vitreous chamber, and deeper anterior chamber than did the persistent hyperopes. In contrast, the persistent emmetropes had a significantly shorter axial length and shallower vitreous chamber depth than did the myopes. Figure 2 presents the spherical equivalent refractive error data across age for each of the four refractive error groups. By definition, the persistent hyperopes remained hyperopic across age, whereas the emmetropizing hyperopes approached the emmetropic group. The spherical equivalent of the myopic group continued to become more myopic until age 14 years.

The best models describing the relation between a given ocular component and age derived from the persistent emmetropes’ data using mixed models with an unstructured variance-covariance matrix are given in Table 4. These models were applied to the data of the other three refractive error groups. The probabilities indicate whether the shape of the model for each of the other three groups (that is, comparisons of the model parameters) differed significantly from that of the persistent emmetropes. Growth curves did not differ when the myopic group was separated into incident and prevalent myopes (data not shown).

There was a decreasing rate of change in all refractive error groups for crystalline lens index (Fig. 3), Gullstrand lens power

<p>| Table 1. Racial/Ethnic Status of Subjects as Classified by Parents |
|-------------------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Racial/Ethnic Group</th>
<th>Myopes n (%)</th>
<th>Emmetropes n (%)</th>
<th>Emmetropizing Hyperopes n (%)</th>
<th>Persistent Hyperopes n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Indian</td>
<td>1 (50.0)</td>
<td>0</td>
<td>1 (50.0)</td>
<td>0</td>
</tr>
<tr>
<td>Asian</td>
<td>59 (72.0)</td>
<td>16 (21.1)</td>
<td>6 (2.4)</td>
<td>1 (1.2)</td>
</tr>
<tr>
<td>African American</td>
<td>1 (33.3)</td>
<td>1 (33.3)</td>
<td>1 (33.3)</td>
<td>0</td>
</tr>
<tr>
<td>Hispanic</td>
<td>4 (26.7)</td>
<td>7 (46.7)</td>
<td>2 (13.3)</td>
<td>2 (13.3)</td>
</tr>
<tr>
<td>White</td>
<td>178 (28.4)</td>
<td>170 (27.1)</td>
<td>240 (38.3)</td>
<td>39 (6.2)</td>
</tr>
<tr>
<td>Other</td>
<td>4 (50.0)</td>
<td>0</td>
<td>3 (37.5)</td>
<td>1 (12.5)</td>
</tr>
</tbody>
</table>

<p>| Table 2. Number of Visits Attended, by Refractive Error Group |
|-------------------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Number of Visits</th>
<th>Myopes n (%)</th>
<th>Emmetropes n (%)</th>
<th>Emmetropizing Hyperopes n (%)</th>
<th>Persistent Hyperopes n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>59 (23.9)</td>
<td>96 (49.5)</td>
<td>21 (8.3)</td>
<td>12 (27.9)</td>
</tr>
<tr>
<td>4</td>
<td>11 (4.5)</td>
<td>14 (7.2)</td>
<td>28 (11.1)</td>
<td>5 (11.6)</td>
</tr>
<tr>
<td>5</td>
<td>15 (6.1)</td>
<td>7 (3.6)</td>
<td>29 (11.4)</td>
<td>5 (7.0)</td>
</tr>
<tr>
<td>6</td>
<td>45 (18.2)</td>
<td>45 (23.2)</td>
<td>42 (16.6)</td>
<td>8 (18.6)</td>
</tr>
<tr>
<td>7</td>
<td>25 (10.1)</td>
<td>3 (1.5)</td>
<td>26 (10.5)</td>
<td>1 (2.3)</td>
</tr>
<tr>
<td>At least 8</td>
<td>92 (37.2)</td>
<td>29 (15.0)</td>
<td>107 (42.5)</td>
<td>14 (32.6)</td>
</tr>
</tbody>
</table>
(Fig. 4), and calculated lens power (Fig. 5), with no statistically significant differences in shape between persistent emmetropes and the other refractive error groups for any of the models. Lens thickness (Fig. 6) showed a decrease in thickness until approximately 9.5 years of age, with an increase in thickness at older ages in all four refractive error groups. There were no differences in model shape for this component as a function of refractive error group.

Persistent emmetropes differed from persistent hyperopes in the shape of the model for anterior chamber depth (Fig. 7). The persistent emmetropes displayed a faster deepening of the anterior chamber at younger ages than did the persistent hyperopes. A difference in the shape of the anterior chamber depth model was also recorded between the myopes and the persistent emmetropes but not between the persistent emmetropes and the emmetropizing hyperopes. The myopes’ anterior chamber depth growth curve had a steeper slope than the growth curve for the persistent emmetropes. The steeper slope indicates that the myopes’ anterior chamber deepening did not slow down with age as much as in the persistent emmetropes. However, the difference was not substantial, as shown by the small differences between parameter estimates. The statistical significance associated with these small differences may be more a function of large sample size.

The persistent emmetropes’ axial elongation (Fig. 8) was significantly slower at older ages in persistent emmetropes than in persistent hyperopes. Myopes also differed significantly in model shape of axial elongation, with the slope of the myopes’ growth curve increasing at a higher rate than the persistent emmetropes after age 10 years. The model shape for axial length did not significantly differ between persistent emmetropes and emmetropizing hyperopes.

For vitreous chamber depth (Fig. 9), myopes and persistent emmetropes differed significantly in model shape. The slope of the vitreous chamber depth growth curve in the myopes in-
increased at a higher rate than in the persistent emmetropes after age 10 years. There were no differences in model shape in the slope of vitreous chamber depth growth curves between the persistent emmetropes and the persistent or emmetropizing hyperopes.

Myopes and persistent emmetropes differed significantly in model shape of corneal power (Fig. 10). Myopes had a relatively constant slope with age, whereas persistent emmetropes had a slope that became increasingly negative with increasing age. Emmetropizing hyperopes also differed from the persistent emmetropes in model shape of corneal power with a slightly increasing slope with age. Persistent emmetropes and persistent hyperopes were not significantly different from each other.

### DISCUSSION

Comparison of the results of this study with previous studies is limited in scope because of the difficulty of comparing growth curves to mean change. Both Gwiazda et al.⁶ (COMET Study) and Fulk et al.⁷ show increases in vitreous chamber depth and axial length in myopes, similar to our myopia curves. The COMET Study also shows similar results in increases in anterior chamber depth. Likewise, there is no change in the corneal radii component from COMET. Over the course of 3 years, there was 0.03-mm change in corneal radii. Our myopia curves show little change in corneal power as well. The one component that seems to be on a different path is lens thickness. The COMET Study shows a mean change in lens thick-

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**Table 4. Best Model to Predict Changes with Age in Emmetropes for Each Ocular Variable**

<table>
<thead>
<tr>
<th>Ocular Component</th>
<th>Models</th>
<th>P</th>
</tr>
</thead>
</table>
| Crystalline lens index | E: 1.427 + 0.162 · age⁻²  
PH: 1.429 + 0.222 · age⁻²  
M: 1.428 + 0.079 · age⁻²  
EH: 1.429 + 0.121 · age⁻² | 0.4645 |
| Gullstrand lens power | E: Age ≤ 9 years 27.001 – 2.983 · ln(age)  
Age > 9 years 25.080 – 2.057 · ln(age)  
PH: Age ≤ 9 years 26.399 – 2.522 · ln(age)  
Age > 9 years 24.408 – 1.654 · ln(age)  
M: Age ≤ 9 years 28.775 – 3.948 · ln(age)  
Age > 9 years 24.311 – 1.945 · ln(age)  
EH: Age ≤ 9 years 25.834 – 2.399 · ln(age)  
Age > 9 years 24.633 – 1.888 · ln(age) | 0.6376 |
| Calculated lens power | E: 21.850 + 153.590 · age⁻²  
PH: 22.501 + 158.168 · age⁻²  
M: 21.244 + 149.618 · age⁻²  
EH: 22.251 + 129.020 · age⁻² | 0.2369 |
| Lens thickness | E: Age ≤ 9.5 years 3.799 – 0.041 · age  
Age > 9.5 years 3.352 + 0.006 · age  
PH: Age ≤ 9.5 years 3.746 – 0.026 · age  
Age > 9.5 years 3.428 + 0.007 · age  
M: Age ≤ 9.5 years 3.841 – 0.046 · age  
Age > 9.5 years 3.389 + 0.002 · age  
EH: Age ≤ 9.5 years 3.778 – 0.036 · age  
Age > 9.5 years 3.363 + 0.007 · age | 0.0954 |
| Anterior chamber depth | E: 1.817 – 0.265 · ln(age)² + 1.441 · ln(age)  
PH: 2.775 – 0.062 · ln(age)² + 0.447 · ln(age)  
M: 1.425 – 0.311 · ln(age)² + 1.749 · ln(age)  
EH: 1.381 – 0.349 · ln(age)² + 1.787 · ln(age) | 0.0048 |
| Axial length | E: Age ≤ 10 years 20.189 + 1.258 · ln(age)  
Age > 10 years 21.353 + 0.759 · ln(age)  
PH: Age ≤ 10 years 19.926 + 0.970 · ln(age)  
Age > 10 years 19.825 + 1.010 · ln(age)  
M: Age ≤ 10 years 18.144 + 2.391 · ln(age)  
Age > 10 years 17.808 + 2.560 · ln(age)  
EH: Age ≤ 10 years 19.660 + 1.566 · ln(age)  
Age > 10 years 21.180 + 0.715 · ln(age) | <0.0001 |
| Vitreous chamber depth | E: Age ≤ 10 years 13.154 + 1.211 · ln(age)  
PH: Age ≤ 10 years 14.754 + 0.513 · ln(age)  
Age > 10 years 12.860 + 1.014 · ln(age)  
M: Age ≤ 10 years 13.437 + 0.762 · ln(age)  
Age > 10 years 11.297 + 2.228 · ln(age)  
EH: Age > 10 years 10.907 + 2.416 · ln(age) | <0.0001 |
| Corneal power | E: 42.131 – 0.566 · ln(age)² + 2.035 · ln(age)  
PH: 45.061 + 0.161 · ln(age)² + 1.033 · ln(age)  
M: 44.253 – 0.009 · ln (age)² + 0.008 · ln(age)  
EH: 44.525 + 0.165 · ln(age)² – 0.704 · ln(age) | <0.0001 |

Comparison models for myopes, persistent hyperopes, and emmetropizing hyperopes based on the best model. The probability is for the comparison between the model for emmetropes and the corresponding refractive error model. E, emmetropes; PH, persistent hyperopes; M, myopes; EH, emmetropizing hyperopes.
ness over 3 years in the single vision lens group of \(-0.01\) mm. In our study, over a similar age range of 6 to 11 years, there appeared to be a decrease in lens thickness of approximately 0.14 mm before a leveling off. A potential reason for this is that our myopic subjects were a combination of pre- and post-onset myopes. The COMET subjects were always myopic. Lens thickness should be studied in more detail before and after the onset of myopia.

Comparisons between the persistent emmetropes and the persistent hyperopes and between the persistent emmetropes and the emmetropizing hyperopes show that the growth curve shapes were similar in the groups, overall, with the exception of anterior chamber depth and axial length. The differences between the persistent hyperopes and the persistent emmetropes were based on the position from which the groups started at baseline. The persistent hyperopes started at a position significantly different from the persistent emmetropes, and their eyes were unable to grow enough to compensate for the smaller size. Therefore, they were unable to emmetropize. Persistent hyperopes had a higher amount of initial hyperopia than did emmetropizing hyperopes.

It is noteworthy to see that the persistent hyperope’s eye grows at all. It would be plausible to think that, because these eyes remain hyperopic, any growth would in fact be absent. Persistent hyperopia does not appear to be an error in growth in childhood, and so the source is more likely to be at sometime earlier in development. Treatments for hyperopia that seek to speed growth may be limited in effectiveness, as the

![Figure 3](https://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933438/) Growth curve for crystalline lens index, using the best model derived from emmetropic data and applying it to the other three refractive groups.

![Figure 4](https://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933438/) Growth curve for Gullstrand lens power, using the best model derived from emmetropic data and applying it to the other three refractive groups.
problem may be more related to the way the eye develops in size in infancy.

Conversely, persistent emmetropes and myopes were similar on almost all variables at baseline, with the exception of greater corneal power for myopes. Their differences appeared for several components in the shape of the growth curves. Components that varied are those related to the size of the eye: vitreous chamber depth, anterior chamber depth, axial length, and corneal power. The two most striking differences between the myopes and persistent emmetropes were in axial length and vitreous chamber depth. In myopes, both of these components had a rate of growth that exceeded that of the persistent emmetropes, with little or no decrease in slope, representing a lack of slowing of the growth as seen in persistent emmetropes as the children reached older ages. Growth in the myopes appeared to continue unchecked. There was little change in the corneal power growth curve of the myopes, whereas the persistent emmetropes experienced a decrease in corneal power over the age range on the order of approximately 0.50 D—an interesting finding. Even in emmetropia, change is going on. The components are not stable. A 0.5 mm growth in axial length, on average, would lead to approximately 1.50 D of myopia without counterbalancing by a change in lens power of a similar amount. These curves help to establish what normal eyes do and show that normal eyes do indeed grow.

The growth curves for myopes contained both prevalent and incident myopes. We analyzed the myopic group based on incident and prevalent myopia (data not presented). The differences between these two groups were a function of that
time at which the subjects entered the study. Growth curves for the incident myopes resembled those of the prevalent myopes but were only offset vertically by the amount of myopia that progressed in the intervening years after onset. However, some caution should be exercised when generalizing the curves to individual myopes due to the difference in age of onset.

Given the similarities of the emmetropic and myopic eye at baseline, it appears the time frame for treatment and prediction before the onset of myopia is relatively short. When the ability to discriminate is limited to a short window in advance of onset, more frequent pediatric eye examinations may be necessary, to catch children at the critical time when onset would be predictable. Effective treatments to prevent or delay onset must also work within a similarly short period.

There is the potential that the shorter follow-up of persistent emmetropes may have had an impact on the curves. Data were available for persistent emmetropes across a range of visits, so the modeling techniques applied should yield robust estimates (data not presented). Given that the persistent emmetropes were older at baseline, some of the length-of-follow-up issue may be related to the study design. The staggered entry at the study’s beginning and cutoff at grade 8 may have yielded emmetropes who were only able to have three or four visits. When we identified a child as an emmetrope at an older age, it was more likely that he or she would continue to remain an emmetrope. Children who were enrolled in grade 6 as an emmetrope had the opportunity to have only three visits. It is also possible that the length of follow-up is related to the lack of incentive for an emmetropic child to continue to participate.
in the study. Because 76% of the emmetropes had their last visits at age 13 or 14, we believe that the more likely reason is the former than the latter. The strict criteria for classifying persistent emmetropes also make them the most susceptible to any measurement variability over the course of the study. Although this has the effect of limiting the size of the emmetrope sample, it would not be expected to introduce bias.

As a follow-up, all the potential growth curve models tested on persistent emmetropic children were applied to each of the components within each of the refractive error groups—that is, a total of 48 models for each refractive error group-component pair. Just as for the persistent emmetropic group, AIC values were used to determine the most appropriate model to relate age and each ocular component within each refractive error group. In several cases, the persistent emmetropic model represented the best model for a refractive error group or component (two models in myopes and one model in emmetropizing hyperopes). For the remaining components, the AIC corresponding to the persistent emmetropic model was often relatively close (within 10%) to the AIC of the best model. There were three cases in which the persistent emmetropic form AIC and the best model differed by more than 10%, which infers that the persistent emmetrope model was not a good fit for that data (models not shown). Therefore, even after forcing the persistent emmetropes’ models on other refractive groups, the models seem to make an accurate representation of change in an ocular component with age.
This growth curve method has many potential applications in the field of vision science. We are currently using it to evaluate the onset of myopia based on time before and after onset to determine changes in components and their relation to its development. It also holds promise for studying the modulation of components in the process of emmetropization, by allowing for a detailed look at the stepwise growth over the period.

CONCLUSIONS
Comparisons of growth curves between persistent emmetropes and three other refractive error groups show that there are many similarities in the growth patterns for both the emmetropizing and persistent hyperopes, while the differences in growth lie mainly between the emmetropes and myopes. Emmetroizing hyperopes and persistent emmetropes have a similar pattern of growth. The curves of the emmetropizing hyperopes represent a middle ground between the persistent emmetropes and persistent hyperopes. This gives a starting point to establish what constitutes “normal” eyes and shows that emmetropic eyes do indeed grow. The relation between the curves of the persistently emmetropic eye and the ametropic eye support the concept that hyperopia and emmetropia are more a product of initial size rather than rate of growth, whereas emmetropia and myopia are distinguished more by growth than initial size.

References