Ocular Component Growth Curves among Singaporean Children with Different Refractive Error Status

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Purpose. To describe and compare ocular component growth curves among different refractive error groups in Singaporean children.

Methods. Data collected yearly in 1775 Asian children aged 6 to 10 years with at least three visits were analyzed. Cycloplegic refractive error and biometry variables were measured by autorefractor and A-scan ultrasound machine. Growth curves were compared between five groups: persistent hyperopia of spherical equivalent (SE) > +1.00 D, emmetropizing hyperopia of SE > +1.00 D on the first visit and between −0.50 D and +1.00 D subsequently, persistent emmetropia of SE between −0.50 D and +1.00 D, incident myopia of SE ≤ −0.50 D at subsequent visits, and persistent myopia of SE ≤ −0.50 D.

Results. The axial length and vitreous chamber elongated faster in the children younger than 10 years, but elongation slowed with age. Growth patterns of axial length and vitreous chamber in the children with newly developed or persistent myopia ($P < 0.01$) showed faster elongation than in the emmetropic children. The anterior chamber deepened until approximately 9 or 10 years of age but became shallower as the myopic and emmetropic children grew older. Conversely, the lens thinned at younger ages and thickened at older ages for all except the persistently hyperopic children.

Conclusions. In young Asian children, the axial length and vitreous chamber depth increased, but the elongation slowed with age. There was a U-shaped growth curve for lens thickness and an inverted U-shaped curve for anterior chamber depth. The findings of early lens thinning followed by thickening suggest a two-phase growth of the lens. (*Invest Ophthalmol Vis Sci.* 2010;51:1341–1347) DOI:10.1167/iovs.09-3431

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Myopia is an escalating public health problem with important socioeconomic implications in many urban Asian countries.[1–3] East Asian urbanized countries including Singapore, Hong Kong, and Taiwan have reported high rates of myopia.[4–6] For example, a nationwide survey of 10,889 Taiwanese children indicated that the prevalence of myopia was 20% at 7 years of age, 61% at 12 years, and 81% at 15 years.[6]

Strategies to prevent or slow myopia are dependent on a clear understanding of the changes in different ocular components, including axial length (AL), in childhood. However, in most studies, the absolute mean changes in ocular components over time have been investigated only in cohorts of myopic children.[7–9] The patterns and characteristics of how different ocular components change among children with myopia compared with those who are emmetropic or hyperopic over extended periods are unclear.

To the best of our knowledge, only the Orinda Longitudinal Study of Myopia (OLSM) which examined 737 children aged 6 to 14 years has compared ocular component growth curves among children with the following refractive characteristics: emmetropia, myopia, emmetropizing hyperopia, and persistent hyperopia.[10] The study showed that children with myopia had a faster rate of axial elongation, deepening of the vitreous chamber, and deepening of the anterior chamber, compared with children with persistent emmetropia. Children with persistent hyperopia had faster axial elongation at older ages, but slower deepening of the anterior chamber at younger ages than did children with persistent emmetropia. It is not known whether this pattern is also present in East Asian children.

We sought to describe and compare ocular component growth patterns among children with persistent emmetropia, persistent myopia, newly developed myopia, emmetropizing hyperopia, and persistent hyperopia in a longitudinal study of Singaporean children.

Methods

All children aged 6 to 10 years from three schools located in the southeastern, western, and northern parts of Singapore were invited to join the Singapore Cohort Study of the Risk Factors for Myopia (SCORM) in 1999 and 2001. The methodology has been published.[11,12] Children with any serious medical or eye disorder, such as congenital cataract were excluded from the study. The parents provided written informed consent. The study was approved by the Ethics Committee of the Singapore Eye Research Institute, and the study's protocol adhered to the tenets of the Declaration of Helsinki.

The children were examined yearly in the schools by a trained team using the same methodology. After the instillation of 0.5% proparacaine, cycloplegia was induced in each eye by administering 3 drops of 1% cyclopentolate solution at 5-minute intervals. Thirty minutes after the last drop of cyclopentolate was instilled, an autokeratorefractor (model RK5; Canon Inc, Ltd., Tochigiken, Japan) was used to obtain the average of five consecutive measures (all readings <0.25 D apart). A biometry ultrasound unit (probe frequency of 10 MHz; Echoscan model US-800; Nidek Co., Ltd, Tokyo, Japan) was used to measure AL, vitreous chamber depth (VCD), anterior chamber depth (ACD), and lens thickness (LT). The average of six measurements was taken with the SD of these six readings being less than 0.12 mm. The average of two corneal radius of curvature (CR) measurements in the flatter and steeper meridians was calculated. The machines were calibrated at the beginning of the study, and all measurements were conducted according to a standard protocol.

Definitions

The spherical equivalent (SE) of the eye was calculated as sphere power + (0.5 × cylinder power). Children were classified into one of five refractive error groups based on the SE of the randomly selected eye: persistent hyperopia, emmetropizing hyperopia, persistent emmetropia, newly developed myopia, or persistent myopia. A child had persistent hyperopia if the SE was more than +1.00 D (exclusive) at all visits. A child who began with hyperopia (SE more than +1.00 D) on at least the first visit but had SE between −0.50 D (exclusive) and +1.00 D (inclusive) at subsequent visits was considered to be a child with emmetropizing hyperopia. A child was deemed to have persistent emmetropia if the SE was between −0.50 D (exclusive) and +1.00 D (inclusive) at all visits. A child who began with emmetropia (SE being between −0.50 D [exclusive] and +1.00 D [inclusive]) on at least the first visit and demonstrated at least −0.50 D (inclusive) at one or more subsequent visits was classified as having newly developed myopia. Persistent myopia was defined as myopia with at least −0.50 D at all visits.

Statistical Analysis

Analyses were performed using data collected yearly when the child was enrolled in elementary school (aged 6–12 years; i.e., from 1999 through 2004 for two schools and from 2001 through 2006 for the third school). Children who had at least three visits between the ages of 6 and 12 years and met the criteria for one of the five refractive error groups were included in the analyses.

Growth curve models of AL, VCD, ACD, LT, and CR were developed using longitudinal data of the randomly selected eye. Fractional polynomial (FP) growth models were fitted for each refractive error group.[13] This method increases the flexibility afforded by the conventional family of polynomials models. The first-degree FP1 function is a power transformation model, $\beta_1 Z^P$, where Z is a single continuous covariate (age, in this analysis) and the powers p are chosen from a restricted set, $S = \{-2, -1, -0.5, 0, 0.5, 1, 2, 3\}$ where Z^0 denotes log Z. The second-degree FP2 is an extension from the FP1 and FP2 functions, with powers p_1, p_2 including the formulations $\beta_1 Z^{P_1} + \beta_2 Z^{P_2}$ and $\beta_1 Z^{P_1} + \beta_2 Z^{P_2} \ln Z$, the latter being a so-called repeated-powers model. The best-fitting model is defined as the model with a p (or combination of p_1 and p_2) that maximizes the likelihood among the FP1 and FP2 models.

To allow for possible nonlinearity in age at all levels of refractive error groups, we used the multivariate fractional polynomial interaction (MFPI) algorithm for investigating interactions between age and refractive error groups.[14] First, the relationship of ocular components and age in the children with persistent emmetropia or persistent hyperopia was modeled by a fractional polynomial (FP) function adjusted for sex, ethnicity, father's education level, and child's height (in centimeters), measured at each time point. The best transformation of age within the class of FP function was selected based on the maximum likelihood, with the constraint of the same powers for the persistent emmetropia and the persistent hyperopia groups. Second, the interaction between the age and the refractive error groups was examined by the likelihood ratio test, and the difference in deviance was compared by χ^{50} test with 2 *df*. These procedures were repeated for pair-wise comparisons between children with persistent emmetropia or emmetropizing hyperopia, persistent emmetropia or newly developed myopia, and persistent emmetropia or persistent myopia for each ocular component. (Statistical analyses were performed with Stata, ver. 10.1; Stata Corp., College Station, TX.)

Results

Of the 1979 children who participated initially in SCORM, 1775 (90%) were included in this analysis (Fig. 1). They were found to be similar in age, sex, ethnicity, and baseline refractive errors when compared with the 204 children who were excluded from the analysis (data not shown).

Based on randomly selected eyes, 1217 of the children were myopic, 616 had persistent myopia, and 601 had newly developed myopia. Forty-seven children were persistently hyperopic, 142 were emmetropizing hyperopes, and 369 were emmetropic throughout the observation period. Table 1 shows that most of the children had enrolled in the study at the ages of 7 (40%) and 8 (32%) years, were male (51%), were Chinese (74%), and had fathers with at least a secondary school education (74%). The persistent myopia and persistent emmetropia (10%) groups had fewer subjects of age 6 at entry, whereas the emmetropizing hyperopia and newly developed myopia (7%) groups had fewer subjects of age 9 at entry. There were slightly more males with persistent emmetropia, whereas more Chinese were found to have newly developed myopia and persistent myopia. More than half the children (64% persistent hyperopia, 70% emmetropizing hyperopia, 61% persistent emmetropia, 73% newly developed myopia, and 53% persistent myopia) had five or six visits.

The fitted FP model of SE refractive error data (in dipoters) for each refractive error group revealed that the SE change was faster in the younger myopic children than in the emmetropic and hyperopic children and slowed down after 10 years of age in all refractive error groups (Fig. 2). We further evaluated the growth curves of height (in centimeters) fitted by the FP model for the five refractive error groups and noted that the increases in height remained constant with age (Fig. 3).

Table 2 shows the best FP growth models of AL, VCD, ACD, LT, and CR for all subjects and in each refractive error group.

The AL of all the children increased as they aged from 7 to 12 years, but the elongation slowed with age (Fig. 4) and tapered off after 10 years of age in all the children. Throughout the period, the longest AL was observed in the children with persistent myopia, followed by those with newly developed myopia, emmetropia, emmetropizing hyperopia, or persistent hyperopia. The axial elongation rate was similar in the children with persistent hyperopia and emmetropizing hyperopia when compared with that in the children with emmetropia. The children with myopia had faster axial elongation than did those with emmetropia, especially if less than 10 years old. Pair-wise comparisons between growth patterns of AL in the children with persistent emmetropia and other refractive error groups suggest that the axial elongation in the children with newly developed myopia ($P < 0.01$) or persistent myopia ($P < 0.01$) was significantly faster than in those with emmetropia, but axial elongation in the children with persistent hyperopia ($P = 0.10$) or emmetropizing hyperopia ($P = 0.20$) was not significantly different from that in emmetropic children, after adjustment for sex, ethnicity, father's education level, and height.

The vitreous chamber grew in a fashion similar to AL (Fig. 5). The children with persistent myopia had the greatest VCD between 7 and 12 years of age, followed by those with newly developed myopia, emmetropia, emmetropizing hyperopia, or persistent hyperopia. In all the children, the vitreous chamber deepened as they grew older, but the deepening tapered off after 10 years of age. A similar rate of deepening of the vitreous chamber was observed among the children who were emmetropic or hyperopic or had emmetropizing hyperopia. The

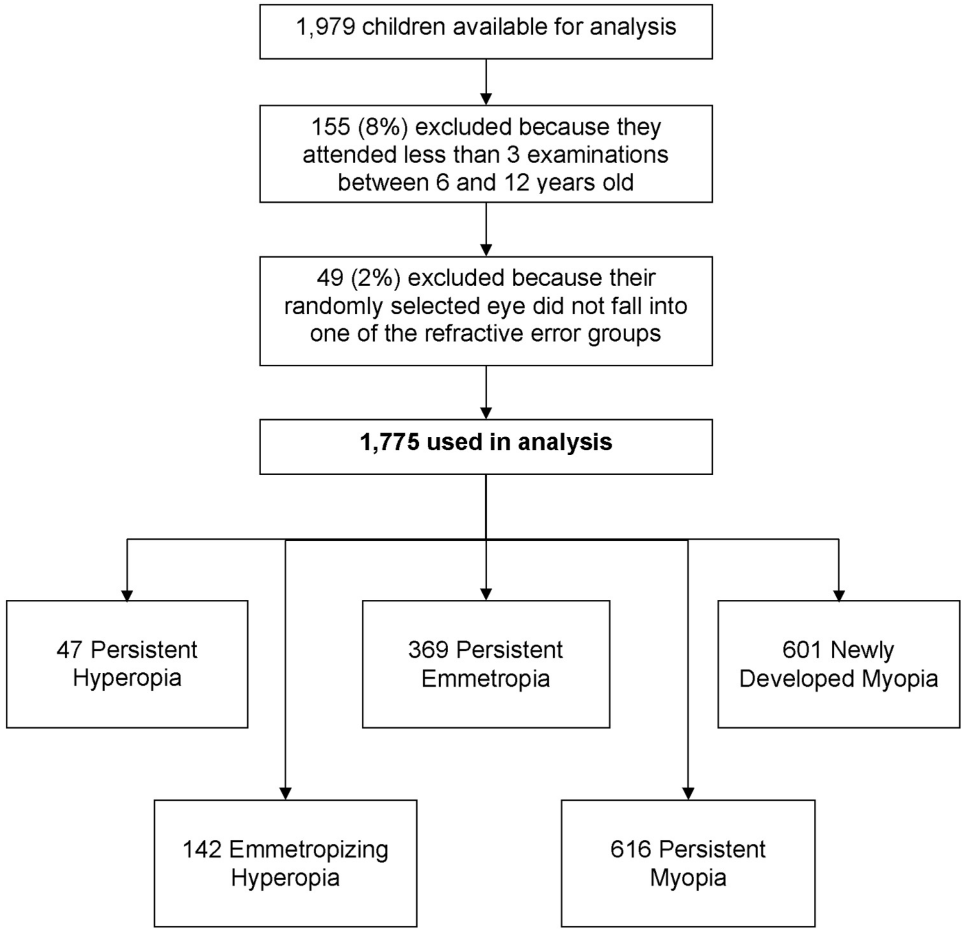

FIGURE 1. Study profile.

children who were myopic and those who had newly developed myopia appeared to have faster deepening of the vitreous chamber than did those who were emmetropic, especially at younger ages. When compared with persistent emmetropia, the children with myopia (newly developed myopia: $P < 0.01$; persistent myopia: $P < 0.01$), but not hyperopia (persistent hyperopia: $P = 0.09$; emmetropizing hyperopia: $P = 0.06$), had significantly faster deepening of the vitreous chamber.

The ACD curves in the children with emmetropia, persistent myopia, or newly developed myopia had an inverted U-shape, whereas the curves in those with persistent hyperopia or emmetropizing hyperopia showed a constant ACD, displayed by a flat line (Fig. 6). The children with persistent hyperopia had the shallowest ACD, followed by the children with emmetropizing hyperopia, throughout the time they were observed. The ACD of the children with persistent emmetropia was slightly deeper than that in the children with newly developed myopia at younger ages, but the ACD became shallower after 8.5 years of age. The children with persistent myopia had the deepest ACD between 7 and 12 years of age. The peak of the ACD curve occurred at ~9 years in the children with emmetropia and at ~10 years in those with persistent myopia or newly developed myopia. ACD in the children with persistent myopia deepened at a faster rate than that in those with emmetropia at younger ages, but the rates were similar after the age of 10 years. The deepening in ACD in the children who had newly developed myopia ($P < 0.01$) was significantly faster at younger ages, but the rate of reduction was slower at older ages compared with that in the emmetropes. This deepening occurred after adjustment for sex, ethnicity, father's education level, and height. However, no significant differences in the growth rates of ACD were observed from the comparisons between the children with persistent emmetropia and other groups (persistent hyperopia: $P = 0.42$; emmetropizing hyperopia: $P = 0.77$; and persistent myopia: $P = 0.66$).

Conversely, the growth of LT followed a U-shaped pattern in all the children, but the pattern in those who were persistently hyperopic was a flat line (Fig. 7). A trough in the LT measurements was observed at ~9 years of age in the children with persistent emmetropia or emmetropizing hyperopia, whereas in those with persistent myopia or newly developed myopia, this trough was observed at ~10 years of age. Children with persistent emmetropia had thinner lenses than did those with persistent hyperopia or emmetropizing hyperopia. When compared with those with newly developed myopia, the lenses of the children who were emmetropic were thicker before 10 years of age, but thinner after that. The thinnest lens was observed in the children with persistent myopia. Similar lens thinning rates were observed in the children with emmetropia or emmetropizing hyperopia at younger ages. However, the rate of lens thickening was faster in the children with emmetropizing hyperopia after the trough than in those with persistent emmetropia. The rate of lens thinning in the children with newly developed myopia was faster than those who were emmetropic in the initial years, and the subsequent thickening of the lens in later years was slower in the children in whom myopia developed. The growth rate of LT in the children with emmetropia differed from that in those with newly developed myopia ($P < 0.01$; persistent hyperopia: $P = 0.85$; emmetropizing hyperopia: $P = 0.55$; and persistent myopia: $P = 0.17$).

Table 1. Characteristics of Children in the Different Refractive Error Groups

Characteristics	PH (*n* = 47)	EH (*n* = 142)	NM (*n* = 601)	PM (*n* = 616)	PE (*n* = 369)	Total (*n* = 1775)
	Refractive Error Groups, *n* (%)*					
Age at entry, y†						
6	8 (17)	30 (21)	129 (21)	58 (9)	37 (10)	262 (15)
7	19 (40)	63 (44)	277 (46)	215 (35)	136 (37)	710 (40)
8	13 (28)	41 (29)	153 (25)	236 (38)	133 (36)	576 (32)
9	7 (15)	8 (6)	41 (7)	104 (17)	62 (17)	222 (13)
10	0 (0)	0 (0)	1 (0)	3 (0)	1 (0)	5 (0)
Sex†						
Male	23 (49)	61 (43)	275 (46)	326 (53)	216 (59)	901 (51)
Female	24 (51)	81 (57)	326 (54)	290 (47)	153 (41)	874 (49)
Ethnicity†						
Chinese	19 (40)	86 (61)	468 (78)	498 (81)	237 (64)	1308 (74)
Malay	18 (38)	30 (21)	67 (11)	56 (9)	87 (24)	258 (15)
Indian	8 (17)	13 (9)	34 (6)	37 (6)	25 (7)	117 (7)
Other	2 (4)	13 (9)	32 (5)	25 (4)	20 (5)	92 (5)
Father's education level†						
No formal education	3 (6)	7 (5)	20 (3)	15 (2)	21 (6)	66 (4)
Primary	17 (36)	37 (26)	132 (22)	129 (21)	118 (32)	433 (24)
Secondary	13 (28)	56 (39)	237 (40)	239 (39)	145 (39)	690 (39)
Pre-university/diploma	5 (11)	21 (15)	102 (17)	104 (17)	45 (12)	277 (16)
Tertiary/university	9 (19)	21 (15)	109 (18)	128 (21)	39 (11)	306 (17)
Visits, *n*†						
3	4 (9)	11 (8)	47 (8)	57 (9)	44 (12)	163 (9)
4	13 (28)	31 (22)	118 (20)	246 (40)	127 (34)	538 (30)
5	17 (36)	50 (35)	196 (33)	164 (27)	116 (31)	543 (31)
6	13 (28)	50 (35)	240 (40)	146 (24)	82 (22)	531 (30)

* PH, persistent hyperopia; EH, emmetropizing hyperopia; NM, newly developed myopia; PM, persistent myopia; PE, persistent emmetropia.
† $P < 0.01$ when comparing the characteristic between refraction error groups.

Between the ages of 7 and 12 years, there were minimal changes in CR in the myopic children (i.e., a flat line for the children with hyperopia or emmetropia; Fig. 8). The children with persistent hyperopia had the largest CR, followed by the children with emmetropia, newly developed myopia, emmetropizing hyperopia, or persistent myopia. The comparison of the growth pattern between the children with persistent emmetropia and other refractive error groups showed no significant differences (persistent hyperopia: $P = 0.91$; emmetropizing hyperopia: $P = 0.36$; newly developed myopia: $P = 0.61$; and persistent myopia: $P = 0.84$).

Discussion

We explored ocular growth curves of a large cohort of Singaporean children who were 6 to 10 years of age at baseline. We found that elongations of AL and VCD were fastest at younger ages and decreased with age in the different five refractive error groups. The growth of AL and VCD in children with hyperopia and emmetropia were similar, but children with newly developed and persistent myopia had faster axial elongation rates than did those with emmetropia, especially the younger children who were less than 10 years of age. We also found that the ACD deepened more rapidly at younger ages but became shallower in both the emmetropic and myopic children when they grew older. In addition, the lenses of all the children, except those with persistent hyperopia showed decreasing thickness until approximately 9 or 10 years of age, with an increase at older ages. Finally, we observed no differences in growth patterns of CR between the emmetropia group and the other refractive error groups.

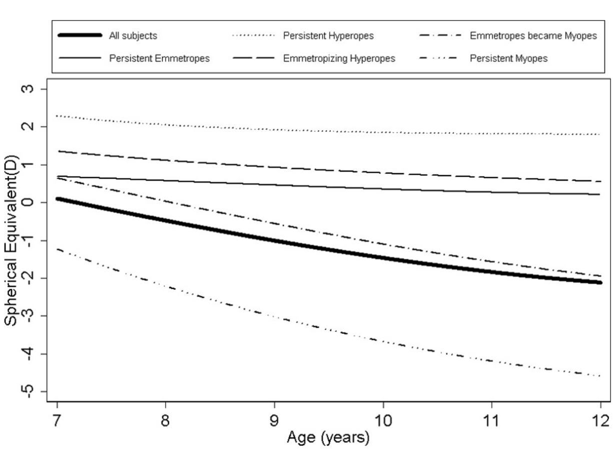

Figure 2. Changes of SE refractive error.

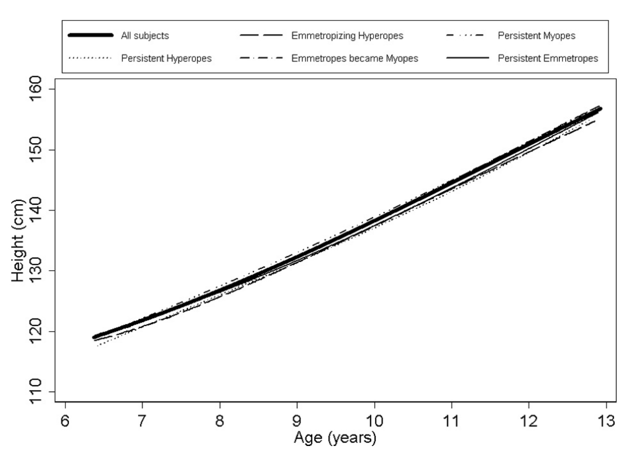

Figure 3. Growth pattern of body height.

TABLE 2. Fractional Polynomial Growth Models for Each Ocular Component

Ocular Components	Growth Models*
AL	
$n = 1771$	ALL, $21.40 + 0.052\ \text{Age}^2 - 0.003\ \text{Age}^3$
$n = 47$	PH, $2.88 - 34.613\ \text{Age}^{-2}$
$n = 141$	EH, $21.79 + 0.006\ \text{Age}^3 - 0.002\ \text{Age}^3 \ln(\text{Age})$
$n = 601$	NM, $20.46 + 0.127\ \text{Age}^2 - 0.040\ \text{Age}^2 \ln(\text{Age})$
$n = 614$	PM, $20.61 + 0.163\ \text{Age}^2 - 0.053\ \text{Age}^2 \ln(\text{Age})$
$n = 368$	PE, $22.25 + 0.005\ \text{Age}^3 - 0.002\ \text{Age}^3 \ln(\text{Age})$
VCD	
$n = 1771$	ALL, $9.88 + 1.789\ \text{Age} - 0.475\ \text{Age} \ln(\text{Age})$
$n = 47$	PH, $15.99 - 40.033\ \text{Age}^{-2}$
$n = 141$	EH, $17.00 - 11.095\ \text{Age}^{-1}$
$n = 601$	NM, $18.81 + 156.817\ \text{Age}^{-2} - 156.164\ \text{Age}^{-2} \ln(\text{Age})$
$n = 614$	PM, $20.83 - 29.811\ \text{Age}^{-1} - 0.025\ \text{Age}$
$n = 368$	PE, $17.18 - 10.045\ \text{Age}^{-1}$
ACD	
$n = 1771$	ALL, $3.43 + 0.002\ \text{Age}^3 - 0.001\ \text{Age}^3 \ln(\text{Age})$
$n = 47$	PH, 3.46
$n = 141$	EH, 3.51
$n = 601$	NM, $3.39 + 0.002\ \text{Age}^3 - 0.001\ \text{Age}^3 \ln(\text{Age})$
$n = 614$	PM, $3.49 + 0.002\ \text{Age}^3 - 0.001\ \text{Age}^3 \ln(\text{Age})$
$n = 368$	PE, $3.44 + 0.001\ \text{Age}^3 - 0.001\ \text{Age}^3 \ln(\text{Age})$
LT	
$n = 1771$	ALL, $7.17 + 1.804\ \text{Age}^{-0.5} - 5.919\ \text{Age}^{-0.5} \ln(\text{Age})$
$n = 47$	PH, 3.48
$n = 141$	EH, $3.74 + 73.455\ \text{Age}^{-2} - 43.491\ \text{Age}^{-2} \ln(\text{Age})$
$n = 601$	NM, $-4.79 + 12.298\ \text{Age}^{-0.5} + 1.882 \ln(\text{Age})$
$n = 614$	PM, $4.04 - 2.092 \ln(\text{Age}) + 1.324\ \text{Age}^{0.5}$
$n = 368$	PE, $3.65 + 58.896\ \text{Age}^{-2} - 34.265\ \text{Age}^{-2} \ln(\text{Age})$
CR of curvature	
$n = 1774$	ALL, $7.76 - 1.107\ \text{Age}^{-2}$
$n = 47$	PH, 7.81
$n = 142$	EH, 7.74
$n = 625$	NM, $7.77 - 0.949\ \text{Age}^{-2}$
$n = 616$	PM, $7.73 - 1.344\ \text{Age}^{-2}$
$n = 364$	PE, 7.79

* ALL, all subjects; PH, persistent hyperopia; EH, emmetropizing hyperopia; NM, newly developed myopia; PM, persistent myopia; PE, persistent emmetropia.

Our findings suggest that the period of rapid growth in AL and VCD was followed by a period of slow growth after 10 years of age, reflecting the slower rates of myopia progression in these children. In contrast, the OLSM in children aged between 6 and 14 years with an SE of at least −0.75 D reported a slower decay in the rate of growth. We noted that the growth curves in the children with myopia in OLSM were based on a combination of the data from both the prevalent and newly developed myopia groups, whereas these two groups were analyzed separately in our study. In SCORM, the changes in SE mirrored the changes in AL and VCD, with faster rates of change in the younger children and slower rates in the older children. However, the increase in height in the Singaporean cohort remained constant with age. The AL and VCD in the children with emmetropia or hyperopia grew at a similar rate, although the rates were slower when compared with those with myopia.[15–19] Comparisons with the OLSM data revealed that growth patterns of AL and VCD in those with emmetropia or hyperopia were faster in younger children and decreased with age in a fashion similar to that in SCORM.[10]

Our results showed an increase in ACD in the children with myopia at younger ages, but it lessened as the children reached 10 years of age (i.e., an inverted U-shaped curve). In the OLSM, however, a continual deepening was found in the anterior chamber in the myopic children, and the deepening slowed with age. The initial increase in ACD in the young children may be a consequence of lens thinning. The decrease in ACD with age in the older children was seen only in the SCORM study and may reflect simultaneous thickening of the lens in the children of the same age. The children with myopia had deeper anterior chambers than did the emmetropic children, a finding that is consistent with the results of previous studies.[20,21] In addition, the faster growth in ACD in younger myopic children

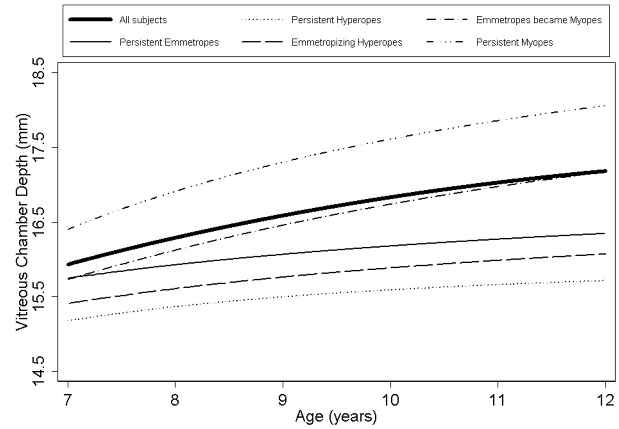

FIGURE 5. Growth pattern of VCD.

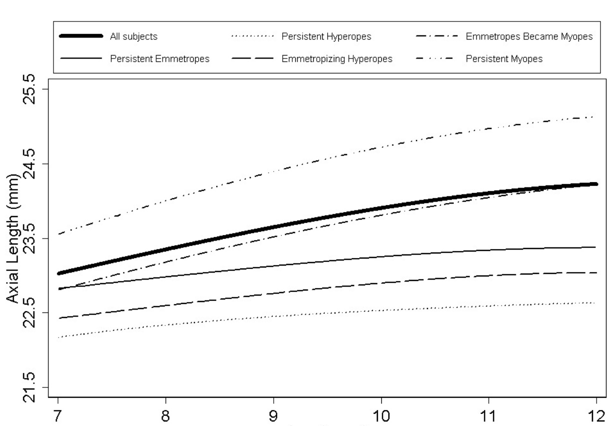

FIGURE 4. Growth pattern of AL.

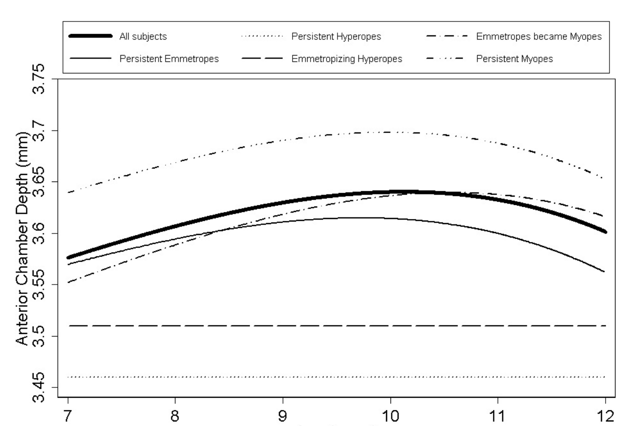

FIGURE 6. Growth pattern of ACD.

compared with that in those with emmetropia was also reported in the OLSM.[10] The Correction of Myopia Evaluation Trial (COMET) documented that the ACD in children with myopia aged 6 to 11 years increased over a 2-year period, with a mean change of 0.035 mm per year.[8] However, only myopic children were included in the COMET study. We found that the ACD was constant in the children with emmetropizing hyperopia, but the growth in LT formed a U-shaped curve. We note that the flat ACD curve may be a result of the small sample size (n = 141) in this group.

The growth patterns of LT in the myopic children were described by an FP function with the convex portion of the curves pointing in the opposite direction. This pattern contrasts with the growth patterns observed for ACD. The decrease in LT until 10 years of age paralleled increases in ACD, suggesting the possibility that the increase in ACD is attributable to the thinning of the lens at the front surface or the rapid growth of AL and VCD at younger ages. Once the growth of AL and VCD was reduced after 10 years of age, ACD lessened, and LT became thicker. Our results pertaining to lens thinning in myopic children agree well with the findings in OLSM[10] and COMET (Norton TT et al. *IOVS* 2008;49:ARVO E-Abstract 2603). The U-shaped curve for LT may be indicative of some early stretching and a thinner lens during the phase of more rapid ocular elongation in the younger children. This stretching was reduced when the child grew older, even though the eye was still elongated (as shown by the slower growth in AL after 10 years of age). The absence of stretching allowed for the lens growth that was always occurring to become evident as the thickening increased. These two phases of growth were suggested by van Alphen[22] and discussed by Mutti et al.[23] Our study also suggests that the trough in LT in the children with myopia occurred at ~10 years, whereas the trough in those with emmetropia occurred at 9 years of age. The trough occurred later in the myopic children in parallel with the slowing of axial elongation in the later years.

The increase in CR between 7 and 12 years of age was minimal in the myopic children. Similarly, the CR in the children with hyperopia and emmetropia remained unchanged. Our results are in good agreement with the previous finding that CR is relatively stable, as the cornea plays little or no role in the process of emmetropization after infancy and early childhood.[24–27]

Comparisons of the growth rates between the children with persistent emmetropia and the children with newly developed myopia showed that all growth patterns were significantly different except for the CR. The difference in growth between the children with persistent emmetropia or persistent myopia was observed only for AL and VCD. These differences in AL and

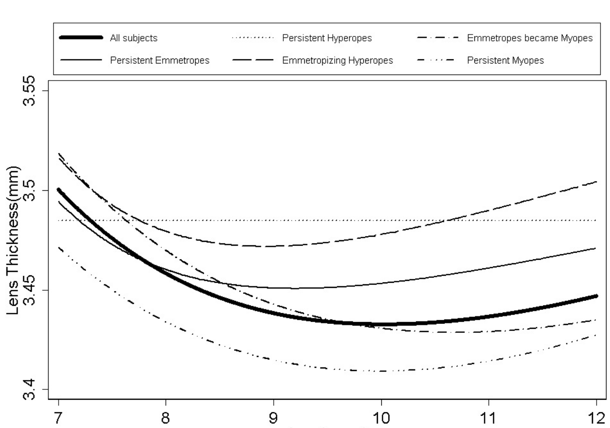

FIGURE 7. Growth pattern of LT.

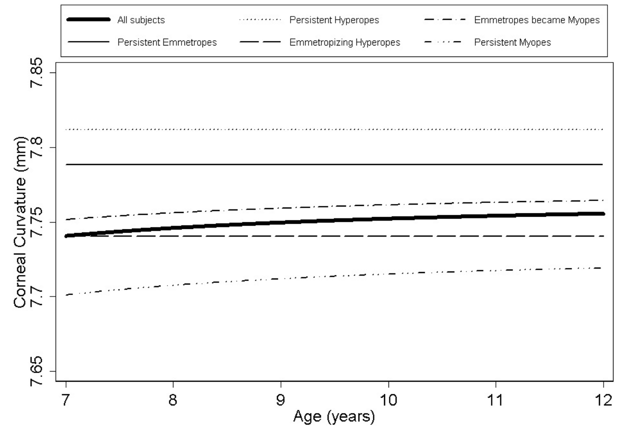

FIGURE 8. Changes of CR of curvature.

VCD were present because myopic eyes had greater AL and VCD. As demonstrated in animal models of myopia, CR remained constant over time, and there were no significant changes in the cornea between the children with persistent emmetropia and those with persistent myopia.[15]

The growth curves of AL, VCD, and CR were similar in the children with hyperopia and emmetropia, but the growth curves of ACD and LT were different. The growth curve of ACD for both hyperopic groups remained constant with age, but the children with emmetropia had an inverted U-shape curve. The children with persistent hyperopia had constant LT, but those with emmetropizing hyperopia had a trough at the age of 9 years, similar to the pattern observed in the children who were emmetropic. However, the differences in the growth patterns of these ocular components were not statistically significant compared with those in the children with hyperopia or emmetropia.

This is the first Asian longitudinal study to compare ocular component growth curves by using FP functions of yearly data between the ages of 7 and 12 years among children with persistent hyperopia, emmetropizing hyperopia, newly developed myopia, persistent myopia, or persistent emmetropia. We distinguished newly developed myopes from persistent myopes, and this distinction allowed us to identify the different rates of growth in ACD and LT among these children, especially those aged 10 years and older. Other strengths of the study include the relatively large sample size and the availability of biometry data over time with a high follow-up rate (90%) of the children with at least three visits. Future studies could include a longer follow-up time from a young age to adulthood.

In summary, our cohort study results show a U-shaped growth curve for LT and an inverted U-shaped growth curve for ACD in Asian children. Our findings of early lens thinning followed by thickening, suggests a two-phase growth of the lens. We also showed that AL and VCD increased with time, with the younger children showing a more rapid elongation that slowed with increasing age. The children with myopia exhibited faster increases in AL and VCD over time compared with those of the emmetropic children.

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References

1. Saw SM, Katz J, Schein OD, Chew SJ, Chan TK. Epidemiology of myopia. *Epidemiol Rev.* 1996;18:175–187.
2. Seet B, Wong TY, Tan DT, et al. Myopia in Singapore: taking a public health approach. *Br J Ophthalmol.* 2001;85:521–526.
3. Wong TY, Foster PJ, Hee J, et al. Prevalence and risk factors for refractive errors in adult Chinese in Singapore. *Invest Ophthalmol Vis Sci.* 2000;41:2486–2494.
4. Wu HM, Seet B, Yap EP, Saw SM, Lim TH, Chia KS. Does education explain ethnic differences in myopia prevalence?—a population-based study of young adult males in Singapore. *Optom Vis Sci.* 2001;78:234–239.
5. Fan DS, Lam DS, Lam RF, et al. Prevalence, incidence, and progression of myopia of school children in Hong Kong. *Invest Ophthalmol Vis Sci.* 2004;45:1071–1075.
6. Lin LL, Shih YF, Hsiao CK, Chen CJ, Lee LA, Hung PT. Epidemiologic study of the prevalence and severity of myopia among schoolchildren in Taiwan in 2000. *J Formos Med Assoc.* 2001;100:684–691.
7. Edwards MH, Li RW, Lam CS, Lew JK, Yu BS. The Hong Kong progressive lens myopia control study: study design and main findings. *Invest Ophthalmol Vis Sci.* 2002;43:2852–2858.
8. Gwiazda J, Hyman L, Hussein M, et al. A randomized clinical trial of progressive addition lenses versus single vision lenses on the progression of myopia in children. *Invest Ophthalmol Vis Sci.* 2003;44:1492–1500.
9. Chua WH, Balakrishnan V, Chan YH, et al. Atropine for the treatment of childhood myopia. *Ophthalmology.* 2006;113:2285–2291.
10. Jones LA, Mitchell GL, Mutti DO, Hayes JR, Moeschberger ML, Zadnik K. Comparison of ocular component growth curves among refractive error groups in children. *Invest Ophthalmol Vis Sci.* 2005;46:2317–2327.
11. Saw SM, Chua WH, Hong CY, et al. Nearwork in early-onset myopia. *Invest Ophthalmol Vis Sci.* 2002;43:332–339.
12. Saw SM, Chua WH, Hong CY, et al. Height and its relationship to refraction and biometry parameters in Singapore Chinese children. *Invest Ophthalmol Vis Sci.* 2002;43:1408–1413.
13. Royston P, Altman D. Regression using fractional polynomials of continuous covariates: parsimonious parametric modeling (with discussion). *Appl Stat.* 1994;43:429–467.
14. Royston P, Sauerbrei W. A new approach to modelling interactions between treatment and continuous covariates in clinical trials by using fractional polynomials. *Stat Med.* 2004;23:2509–2525.
15. Curtin BJ. *The Myopias: Basic Science and Clinical Management*. Philadelphia: Harper and Row; 1985:277–385.
16. Lam CS, Edwards M, Millodot M, Goh WS. A 2-year longitudinal study of myopia progression and optical component changes among Hong Kong schoolchildren. *Optom Vis Sci.* 1999;76:370–380.
17. Mutti DO, Sholtz RI, Friedman NE, Zadnik K. Peripheral refraction and ocular shape in children. *Invest Ophthalmol Vis Sci.* 2000;41:1022–1030.
18. Schmid KL, Li RW, Edwards MH, Lew JK. The expandability of the eye in childhood myopia. *Curr Eye Res.* 2003;26:65–71.
19. Strang NC, Schmid KL, Carney LG. Hyperopia is predominantly axial in nature. *Curr Eye Res.* 1998;17:380–383.
20. Hosaka A. The growth of the eye and its components: Japanese studies. *Acta Ophthalmol Suppl.* 1988;185:65–68.
21. McBrien NA, Millodot M. A biometric investigation of late onset myopic eyes. *Acta Ophthalmol (Copenh).* 1987;65:461–468.
22. van Alphen GW. Choroidal stress and emmetropization. *Vision Res.* 1986;26:723–734.
23. Mutti DO, Hayes JR, Mitchell GL, et al. Refractive error, axial length, and relative peripheral refractive error before and after the onset of myopia. *Invest Ophthalmol Vis Sci.* 2007;48:2510–2519.
24. Fledelius HC. Ophthalmic changes from age of 10 to 18 years: a longitudinal study of sequels to low birth weight. IV. Ultrasound oculometry of vitreous and axial length. *Acta Ophthalmol (Copenh).* 1982;60:403–411.
25. Fledelius HC. Ophthalmic changes from age of 10 to 18 years: a longitudinal study of sequels to low birth weight. III. Ultrasound oculometry and keratometry of anterior eye segment. *Acta Ophthalmol (Copenh).* 1982;60:393–402.
26. Zadnik K, Mutti DO, Friedman NE, Adams AJ. Initial cross-sectional results from the Orinda Longitudinal Study of Myopia. *Optom Vis Sci.* 1993;70:750–758.
27. Mutti DO, Mitchell GL, Jones LA, et al. Axial growth and changes in lenticular and corneal power during emmetropization in infants. *Invest Ophthalmol Vis Sci.* 2005;46:3074–3080.