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Ocular Component Development during Infancy and Early Childhood

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Abstract

Significance: The study fills an important gap by providing a longitudinal description of development of the major structural and optical components of the human eye from 3 months to nearly 7 years of age. Normative development data may provide insights into mechanisms for emmetropization and guidance on intraocular lens power calculation.

Purpose: Describe the pattern of development of refractive error and the ocular components from infancy through early childhood.

Methods: Cycloplegic retinoscopy (cyclopentolate 1%), keratophakometry, and ultrasonography were performed longitudinally on between 162 and 293 normal birthweight infants at 0.25, 0.75, 1.5, 3, 4.5, and 6.5 years of age.

Results: Refractive error and most ocular components displayed an early exponential phase of rapid development during the first 1–2 years of life followed by a slower quadratic phase. Anterior and vitreous chamber depths, axial length, and crystalline lens radii increased at every visit. The crystalline lens thinned throughout the ages studied. The power of the cornea showed an early decrease, then stabilized, while the crystalline lens showed more robust decreases in power. The crystalline lens refractive index followed a polynomial growth and decay model, with an early increase followed by a decrease starting at 1–2 years of age. Refractive error became less hyperopic, then was relatively stable after 1–2 years of age. Axial lengths increased by 3.35 ± 0.64 mm between ages 0.25 and 6.5 years, showed uniform rates of growth across the range of initial values, and were correlated with initial axial lengths ($r = 0.44$, $P < 0.001$).

Conclusions: Early ocular optical and structural development appears to be biphasic, with emmetropization occurring within the first 2 years of infancy during a rapid exponential phase. A more stable refractive error follows during a slower quadratic phase of growth when axial elongation is compensated primarily by changes in crystalline lens power.

Keywords

emmetropization; refractive error; infant vision; ocular development

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The rapid rate of growth of the infant eye in the first years of life is well established.[1–4] During this time, the deepening of the anterior chamber and axial elongation are coordinated with flattening of the cornea and decreases in the power of the crystalline lens to reduce the average level of hyperopia and the variation in early refractive errors.[4] The majority of this process of emmetropization takes place within the first two years of life.[5–9] Refractive errors then become relatively stable despite continued growth of the eye until later in childhood and early adolescence when myopia has its peak incidence.[10] Infant biometry data are useful for understanding the interplay between ocular components during the emmetropization process. These data may also guide surgeons in determining the intraocular lens (IOL) power to use after removal of cataracts in infancy. The refractive error target may be emmetropia immediately after surgery or some amount of residual hyperopia that would be managed with contact lenses and/or glasses until axial elongation places the eye closer to emmetropia at an older age.

Selection of the target for residual hyperopia post-IOL implantation requires knowledge of the amount of axial elongation to follow. Reductions in corneal power are less relevant because they are relatively small and tend to happen very early in infancy.[4, 11–13] While the literature suggests that IOL power calculation produces reliable refractive error outcomes immediately post-surgery, there is considerable variation that develops over the longer term. The average difference between the target and the actual refractive error in the immediate post-operative period for pediatric cataract surgeries is on the order of 0.5 D to 1.5 D with standard deviations of 1.0 D to 2.5 D.[14–18] This relative accuracy at the time of surgery is in contrast to the varying amounts of change in refractive error that occur following IOL implantation in infants. Some studies report very little change for most patients[19, 20] while others show a wide range that include hyperopic shifts at one extreme and 10-D,[21, 22] 20-D, [23] or larger myopic shifts at the other.[24] Making an accurate long-range prediction of post-surgical refractive error is clearly more difficult than calculating a target IOL power.

Two studies often used to predict future axial growth are a cross-sectional series of 148 eyes of 79 normal, phakic subjects[25] and a longitudinal study of 156 aphakic eyes that underwent cataract removal before age 10 years.[26] Despite their proven usefulness, these studies have an important limitation in that they do not provide an estimate of the variation in growth that may occur over time. Any individual departure from the growth pattern for the average eye will necessarily increase the variation in refractive error in the years following surgery. Some of this variation may be individual but the impact of other factors may be more systematic. One of the more important candidate factors is the effect of initial axial length. Do shorter eyes in infancy follow the same growth trajectory as longer eyes? Initial length will also create different optical effects as the eye elongates. As McClatchey and co-workers have pointed out, effectivity will amplify the optical impact of elongation in shorter vs. longer eyes; the myopic shift per millimeter of axial elongation is greater for a smaller eye than for a larger one.[23] Few longitudinal infant biometry datasets exist to provide estimates of the variation in axial elongation or that describe the effects of initial axial length.[3, 27, 28] Data from a sample of 20 full-term infants measured multiple times in the first year of life by ultrasonography and recent results for unoperated eyes from the Infant Aphakia Treatment Study show no significant differences in growth rate based on initial axial length. [3, 27] In contrast, MRI measurements of axial length at 5–17 days of life followed by

IOLMaster axial length data at age 3 years suggest that initially large eyes grow more slowly and small eyes more rapidly, resulting in no significant correlation between axial lengths prior to 3 weeks of age and those at 3 years.[28]

The purpose of the current analysis is to use longitudinal data on all major ocular optical components, including keratometric and crystalline lens power, over a range of ages from infancy to childhood in order to provide average component growth curves, to describe the amount of variation in component development, particularly axial elongation, between infancy and early childhood, and to examine whether that variation can be accounted for by other baseline variables such as initial axial length or keratometric power.

METHODS

Methods used in the study have been published in detail previously.[4] In brief, subjects for the Berkeley Infant Biometry Study (BIBS) were recruited from diaper service newsletter advertisements, word-of-mouth, and invitation letters sent to new parents identified from Contra Costa County, CA, birth records. Parents provided written informed consent according to the tenets of the Declaration of Helsinki after all procedures were explained. The BIBS protocol was reviewed and approved by the Institutional Review Boards for The Ohio State University, the University of California, Berkeley, and the State of California. Inclusion criteria were both genders, all refractive errors (including emmetropia), birthweight over 2500 grams, confirmation that the baby was under the general care of a pediatrician, no history of difficulty with pupil dilation, and no previous or active cardiac, liver, respiratory, or ocular disease. An existing strabismus was allowable, although no baby entered the study with strabismus.

All reported biometric measurements were performed on the right eye only. Refractive error was the average spherical equivalent measured by two observers masked to each other's cycloplegic retinoscopy findings (one drop of proparacaine 0.5%, followed by two drops of cyclopentolate 1.0% in each eye with five minutes between cyclopentolate drops). Keratometric corneal power was measured from Purkinje image reflections recorded by a custom hand-held video camera.[29] Crystalline lens radii of curvature, power, and equivalent refractive index were calculated from an individual schematic eye created for each subject using ocular biometric data and Purkinje image reflections from the crystalline lens captured with the same camera.[30] Ocular axial dimensions were measured with a Humphrey 820 A-scan ultrasound (Humphrey Instruments, Dublin, CA). Measurements were taken over the closed eyelid in semi-automatic mode using the "dense cataract" setting at 100% gain. The measurement trace was digitized, the posterior corneal peak identified, the corneal and eyelid thickness subtracted, and then 500 microns of corneal thickness was added back in order to provide a measurement of anterior chamber depth.[31]

This report analyzes data from up to 293 out of 302 children with between 1 and 7 study visits (52.6% female). The ethnic distribution of the sample was 206 (70.3%) white, 22 (7.5%) Asian-American, 11 (3.8%) African-American, 6 (2.0%) Filipino, 2 (0.7%) East Indian, 2 (0.7%) Native American, 14 (4.8%) other, and 30 (10.2%) who declined to state. Nine subjects were excluded from analysis because they were uncooperative and unable to

provide complete data at baseline (7), had a low birthweight (1), or received the incorrect cycloplegia (tropicamide instead of cyclopentolate (1).

The target age for the initial visit was 3 months (n=293; 0.25 yrs) after birth, followed by visits at 9 (n=278; 0.75 yrs), 18 (n=264; 1.5 yrs), 36 (n=243; 3 yrs), 54 (n=162; 4.5 yrs), and 78 months (n=196; 6.5 yrs; Table 1). The average age was close to target for visits 3, 4, and 6 and about 2 weeks older than the target for visits 1, 2, and 5.

Growth models were fit using the NLMIXED procedure in SAS version 9.3. Candidate growth curve models included polynomial, exponential, a combination of exponential and polynomial, and double exponential forms. These parametric growth curves were evaluated using the Akaike Information Criterion in addition to being checked against unbiased, non-parametric running averages for goodness of fit. Growth curves for 8 of the 10 variables were best fit by an early exponential growth or decay function followed by a quadratic curve as age increased (Equation 1). Of these 8, all but refractive error included a sex-dependent term (male = 0, female = 1). The variable T in each equation equals (age – 0.25) and represents age in years centered on 3 months (0.25 years). This step simplifies the equation if the initial visit age were exactly 3 months by making T equal to zero, allowing the sum $(\beta_1 + \beta_3)$ to represent an estimated baseline component value for a male and $(\beta_1 + \beta_2 + \beta_3)$ for a female at this target age.

$$\text{Ocularvariable} = \left[\beta_1 + \left(\beta_2 * Sex\right)\right] + \left(\beta_3 * e^{-\beta_4 * T}\right) + \left(\beta_5 * T\right) + \left(\beta_6 * T^2\right)$$

The growth curve for the posterior lens radius of curvature (PLC) also included a sex-dependent modification of the coefficient in the exponential portion of the equation, but had no significant quadratic coefficient.

$$\text{PLC} = \left[\beta_1 + \left(\beta_2 * Sex\right)\right] + \left(\left[\beta_3 + \left(\beta_7 * Sex\right) * e^{-\beta_4 * T}\right]\right) + \left(\beta_5 * T\right)$$

Lens equivalent refractive index was fit with a polynomial growth and decay model, a function with an early rise that was followed by a fall at older ages, with no sex-dependent terms.

$$\text{Lensindex} = \beta_1 + \left[\left(\beta_2 * (1+T)^{\beta_3}\right) / \left(100 + \left(\beta_4 * (1+T)^{\beta_5}\right)\right)\right]$$

Axial length at the final visit (target age 6.5 years) as a function of axial length at baseline (target age 3 months) was examined using orthogonal regression (JMP, v. 10, Cary, NC). Residuals from that regression were then checked for any association with initial keratometer power.

RESULTS

The average (±SD) age and values for each of the ocular component variables at each visit are given in Table 1. The number of subjects in Table 1 varies by measurement and visit. The simplest measurement, retinoscopy, was done on each of the children. Ultrasound could not be done on some subjects because of crying or poor cooperation. Phakometry data depend on ultrasound data and were therefore missing whenever ultrasound data were missing. All components underwent substantial amounts of change between 3 months and 6.5 years of age (Tables 1 and 2). Table 1 presents results from all subjects while Table 2 presents results from up to 153 subjects seen within the age window and with data at both 3 months (±1 month) and 6.5 years (±6 months). The power of the cornea decreased by about 1.5 D while the power of the crystalline lens decreased by a far greater amount on average, nearly 14 D. The crystalline lens underwent axial thinning by 0.3 mm along with flattening of each lens surface with age. The equivalent refractive index of the crystalline lens showed no substantial net change between 3 months and 6.5 years of age. The optical effects of these power losses, a shift toward hyperopia, were offset by deepening of the vitreous chamber and an increase in overall axial length. The net effect on refractive error was a reduction in hyperopia by about 1 D, from roughly +2.0 D at 3 months to +1.0 D at 6.5 years of age.

Ocular component values at age 6.5 years were significantly correlated with initial values at 3 months with the exception of lens equivalent refractive index (Table 2). The signs on the significant correlations were all positive, indicating that individual subjects with relatively higher powers for the cornea and crystalline lens, longer, deeper axial dimensions, and more hyperopic refractive errors at the earliest visit tended to retain them during development. Ocular component values were also inter-correlated at 3 months of age (Table 3). Other than the expected high correlations between axial length and its component parts (anterior chamber depth and vitreous chamber depth), some of the stronger correlations were between a shorter axial or vitreous length and a steeper, more powerful cornea and crystalline lens.

All parametric growth curves were close approximations of their non-parametric running averages. The best-fit equations with their coefficients are given in Table 4. The curves are shown as bold black lines superimposed over the individual data in Figure 1 (axial dimensions) and Figure 2 (radii of curvature, refractive powers, and refractive error). Sex differences were small and are not shown for clarity. These differences can be found from the coefficients for sex in the growth curve equations in Table 4. Females had smaller axial dimensions and steeper, more powerful ocular refracting surfaces. For example, females had shorter axial and vitreous lengths by about 0.3 mm, but more powerful corneas and crystalline lenses by 0.7 D and 1.0 D, respectively. The early exponential phase dominated early development but transitioned to the quadratic growth generally by 1–2 years of age. The polynomial growth and decay model for equivalent refractive index of the crystalline lens displayed more complex behavior, with increases at younger ages followed by decreases in older children to result in no substantial net change in equivalent refractive index between 3 months and 6.5 years of age. Early increases in refractive index would dampen the reduction in lens power from surface flattening while later decreases would enhance the reduction in lens power. Refractive error and corneal power were the most stable of the ocular components after about 18 months of age.

One noteworthy feature of the increases in axial length, and even more so for vitreous chamber depth, was the general uniformity of the rate of change across subjects (Figure 1). We explored this feature in greater detail using orthogonal regression between axial length at 6.5 years as a function of initial axial length at 3 months. The slope was not significantly different from 1.0 (β = 1.2, 95% CI: 0.85 – 1.7), suggesting a uniform amount of change across baseline eye lengths. The generally uniform change in axial length between 3 months and 6.5 years had no significant association with initial keratometric power.

Even though initial axial length did not appear to influence its subsequent rate of growth, the range of baseline axial lengths has implications for identifying a target post-surgical refractive error that will lead to the desired refractive error in childhood. Optical effectivity will produce a different shift in refractive error per millimeter of elongation depending on the initial length of an aphakic or pseudophakic eye. Shorter eyes will undergo a greater myopic shift per mm of elongation than longer eyes.[23] This effect was modeled using vergence equations and values across the range of axial lengths from the current study data for 3-month-old infants and 6.5-year-old children. The IOL was assumed to be a thin lens. Corneal power was assumed to be 43.9 D and 42.4 D for 3 month-old infants and 6.5 year-old children, respectively (Table 1). Pseudophakic anterior chamber depth was assumed to be 3.5 mm and 4.1 mm for 3 month-old infants and 6.5 year-old children, respectively.[25,32]

A range of IOL powers between +20 D and +37 D would be needed to create a refractive error of +6.00 D 3 months of age (Figure 3A). This target level of hyperopia in infancy would not be sufficient to produce emmetropia in childhood as all calculated refractive errors at age 6.5 years were myopic. The predicted refractive error at 6.5 years of age resulting from 3.4 mm of elongation ranged from roughly −2.00 D at the longest initial axial lengths to −5.00 D at the shortest initial axial lengths (Figure 3B). IOL powers would need to be in the range of +16 D to +28 D and post-surgical hyperopia would need to be in the range of +11 D to +14 D to produce emmetropia at age 6.5 years (Figures 3A and 3B).

DISCUSSION

This large, longitudinal dataset provided average growth curves for refractive error and each of the major ocular optical components that determine refractive error. Axial dimensions were in general agreement with previous work. The initial average value of 19.2 mm for axial length was similar to values obtained from MRI[33] but 1–2 mm longer than those from other studies that included infants at 3 months of age.[3, 25, 34] The value of 22.4 mm for axial length at 6.5 years was similar to MRI and ultrasound results for children of that age.[25, 34, 35] The pattern of rapid early elongation followed by slower growth at older ages was very similar to that found in previous studies, as was the growth by about 3.4 mm in axial length between 3 months and 6.5 years of age.[3, 25, 33, 34] Anterior chamber depth underwent a small and rapid increase very early,[33, 36] but unlike the asymptote seen in MRI results,[33] there was a very slow but continual increase of a few tenths of a mm throughout infancy and early childhood. Lens thinning previously reported in infancy was also seen in the current study on a very small scale of 0.3 mm between 3 months and 6.5 years of age.[37] Lens thinning was not found in MRI results, but that technique may not have the resolution to detect these small changes in anterior chamber depth and lens thickness.[33]

The keratometric power of the cornea in the current study and the pattern of an early decrease by about 1.5 D followed by stability at 1–2 years of age was similar to that reported by others.[12, 25, 33] The corneal radii obtained using MRI appear to be steeper throughout the range of ages in the current study.[33] Radii of 6.75 – 7.25 mm would correspond to more powerful keratometry readings in the range of 50.0 – 46.5 D. The anterior lens radii of 5 – 9 mm from MRI are also steeper than the average values of 7.3 – 12.3 mm from phakometry found in the current study, as are the posterior lens radii (4.0 – 5.5 mm from MRI compared to 4.7 – 6.3 from phakometry).[33, 38] Phakometry samples lens curvature using reflections from the apical, paraxial portion of the crystalline lens while curvature from MRI is derived by curve fitting across the entire surface of the crystalline lens visible in MRI. The source of the discrepancy is difficult to identify. The shape of the crystalline lens is nearly spherical in the MRI data,[38] making it unlikely that inclusion of peripheral lens surface in MRI would bias values relative to apical lens radii in phakometry. Lens thickness from MRI agrees well with that from ultrasound, making it unlikely that some smaller, steeper form of the lens is being evaluated in MRI.[33, 38]

The data from Gordon and Donzis capture the decrease in lens power that takes place as the eye elongates, but the range of powers between infancy and childhood are low compared to the current study.[25] Their calculated powers changed from roughly 29 D for infants under 1 year of age to 19 D for children between 6 and 7 years of age where the current study found average powers starting at 40 D that became 27 D by age 6.5 years. The source of the discrepancy is again difficult to identify. Axial length and keratometric values are similar for the two studies, but the assumed anterior chamber depth is not given for their simulated posterior chamber IOL lens power. Perhaps their assumed chamber depth was shallow as that would make a lower lens power more effective optically.

The crystalline lens refractive index showed a complex pattern of growth and decay, increasing after 3 months of age to reach a maximum at 1–2 years of age, followed by decreases to levels slightly below those seen at baseline. These changes would alter refractive error by nearly 3 D. The implications of this change in direction on refractive error development are unclear. One possibility that requires further evaluation is that emmetropization is enhanced during the early phase when refractive index increases would help to reduce early hyperopia. The second phase may assist with maintaining emmetropia as refractive index decreases would help to reduce lens power and keep refractive error stable within the growing eye. The timing of this change in direction for crystalline lens refractive index between 1–2 years of age is interesting given that it coincides with emmetropization being largely complete by 18 months.[8, 9, 39]

Robust development took place between infancy and early school age with differing degrees of variability between ocular components. The average amount of change was roughly equal to the magnitude of the standard deviation for the change in refractive error, but was 5–6 times larger than the standard deviation for change in axial length, vitreous chamber depth, and lens power (Table 2). The question of whether or not early component values are correlated with those at older ages is an important one considering that strong correlations will make for better predictions of future component values. A recent report from the Growing Up in Singapore Towards healthy Outcomes (GUSTO) study found no significant

correlation between MRI axial lengths taken 5–17 days after birth and IOLMaster axial lengths of the same children at 3 years of age.[28] In contrast, 9 out of 10 ocular variables in the current study showed significant positive correlations between values at 3 months of age and those at 6.5 years of age (Table 2). The later final age in the current study compared to GUSTO was probably not the reason for the different result; the correlation in BIBS data between initial values of axial length was 0.44 for values at 6.5 years and 0.53 for values at 3 years (both $P < .001$). A change in axial length measurement technique in GUSTO may have reduced the correlations, although average values for axial length taken from MRI agree with those from ultrasound, and ultrasound values show good agreement with those using the IOLMaster.[40, 41] The current study has the advantage of using the same technique at both ages. Another possibility is that the correlations seen in the current study only develop close to 3 months of age and axial length measurements in GUSTO were too early to see these correlations with later values.

The two studies also disagree on the effect of initial axial length on the rate of elongation. GUSTO found that longer eyes at baseline grew more slowly and shorter eyes grew more rapidly while the current study results are that axial length increased uniformly by about 3.4 mm across the range of initial lengths. Regression to the mean is one possible explanation for this discrepancy. Eyes might be long at baseline in part due to measurement error that is not present at a later visit, giving the impression of slower growth for initially longer eyes, and *vice versa*, as found in GUSTO. We checked our data for this possibility by grouping axial length into quartiles based on three different visits (3 months, 9 months, and 6.5 years), then looked at the difference between initial and final axial length within each quartile. Consistent with regression to the mean, the pattern depended on which visit was used for grouping. When grouped based on the initial visit, axial elongation for the largest eyes was slower than for the smallest eyes and *vice versa*. The opposite pattern occurred when grouped based on the final visit. However, elongation was nearly uniform across quartiles between 3 months and 6.5 years when the quartiles were based on 9-month axial lengths. Given the strong possibility of regression to the mean, the simplest prediction for axial length at 6.5 years would be to add a constant 3.4 mm to the initial axial length. Keratometry data were not useful for predicting a final value for axial length. The generally uniform, parallel development across initial axial lengths seen in the current study is consistent with the pattern reported for normal eyes in the Infant Aphakia Treatment Study (IATS).[27]

While a predictive model for selecting an IOL power during infant cataract surgery sounds useful, one fundamental limitation is that axial elongation in the operated eye in cases of unilateral cataract seems more variable than in normal eyes. Results from IATS show a wider range of values and more variability in individual slope for axial elongation in operated compared to normal fellow eyes.[27] Refractive errors at 5 years of age had a median value of −2.25 D but extended over a 24 D range.[24] The myopic value might be expected considering the post-surgical mean (±SD) prediction error was 1.0 ± 2.0 D less hyperopic than intended.[17] The wide range was attributed primarily to the “inability to accurately predict the degree of axial elongation”.[24] Axial growth in these eyes may be affected by the IOL haptics,[42] defocus,[43] and amblyopia.[44] Another factor that may have contributed to variability in the final refractive error was using a set refractive error as a post-operative goal. This strategy does not properly account for the impact of effectivity depicted in Figure

3. A better strategy might be to set a post-operative refractive error goal that incorporated the optical effects of the predicted mm of axial elongation given the initial length of the eye. One disadvantage of this approach is that the post-surgical amount of hyperopia would have to be considerable for initially smaller eyes, creating more post-surgical anisometropia and a greater challenge for optical correction. Even diligent optical management of the anisometropia may not be sufficient to prevent amblyopia, as evidenced by the poor acuity of patients in IATS.[24] Ignoring effectivity and targeting a single post-operative refractive error at 3 months of age would only create about a 3.5 D range of refractive errors at 6.5 years of age (Figure 3), far less than the range found in IATS and other studies.[19–24] The unpredictability of axial elongation in eyes affected by unilateral cataract in infancy appears to be the major factor creating variability in childhood refractive error in these patients.

In summary, the development of most ocular optical components and refractive error could be described from infancy through early childhood by functions combining exponential and quadratic forms. Early rapid increases in axial dimensions and crystalline lens radii of curvature during the exponential phase were followed by slower increases in the quadratic phase. Early rapid decreases in corneal and crystalline lens power were followed by slower decreases in the quadratic phase. The refractive index of the crystalline lens was an exception, with an early exponential rise followed by a later exponential decay. Most component values in infancy were correlated with their values in early childhood. Axial elongation added roughly 3.4 mm to initial lengths with some variability (SD = ± 0.64 mm) that was unrelated to either initial axial length or keratometer power. Prediction of future axial length may aid surgeons in choosing an IOL power to implant after removal of a cataract in infancy, particularly if optical effectivity is considered. However, high levels of variability in a final refractive error will likely still occur in these cases because of their inconsistent, less predictable rates of axial elongation compared to eyes without cataract.

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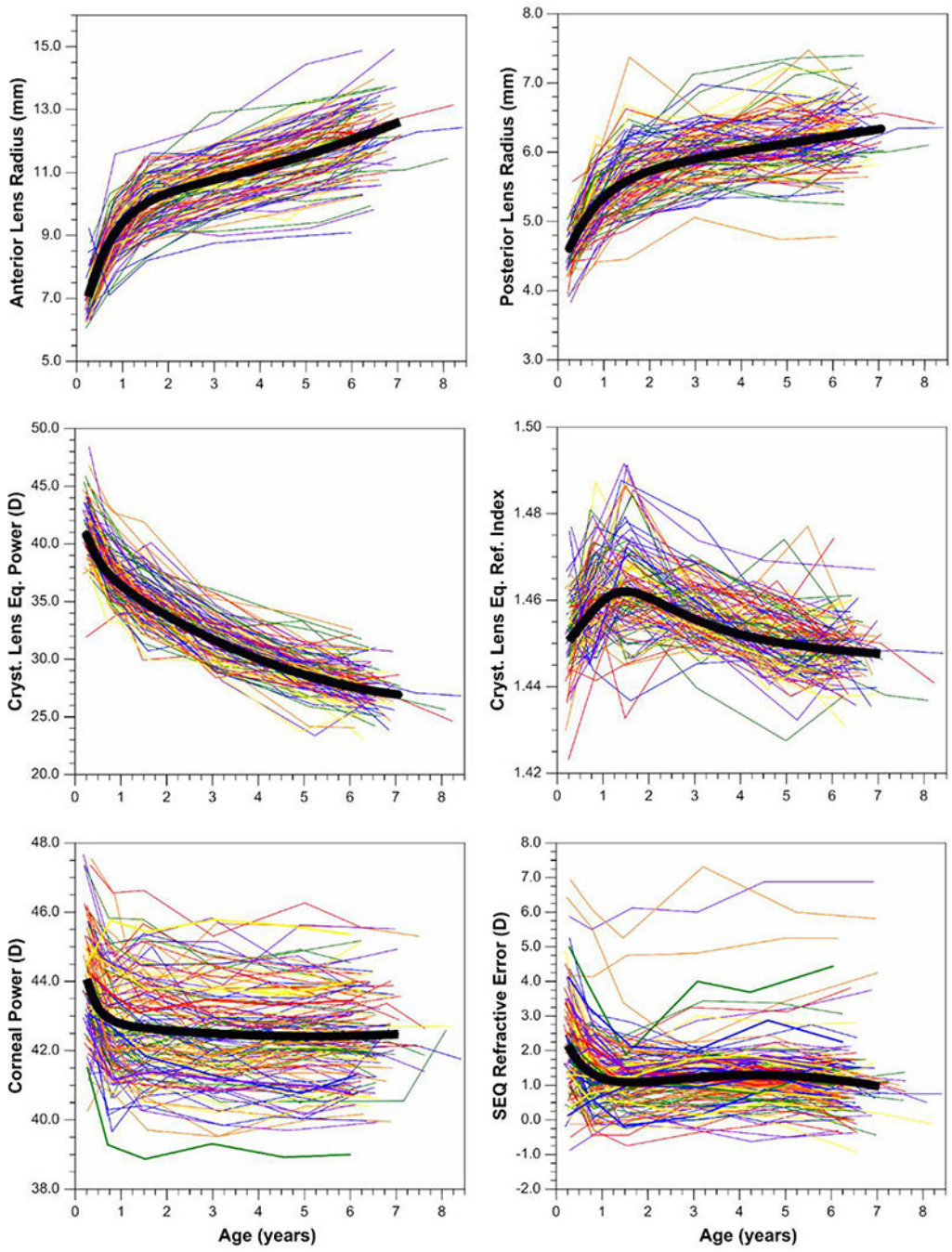

Figure 1. Growth curves (bold black line) for each axial dimension superimposed over the individual data.

Visit data points are connected by lines to make following the development of individuals easier.

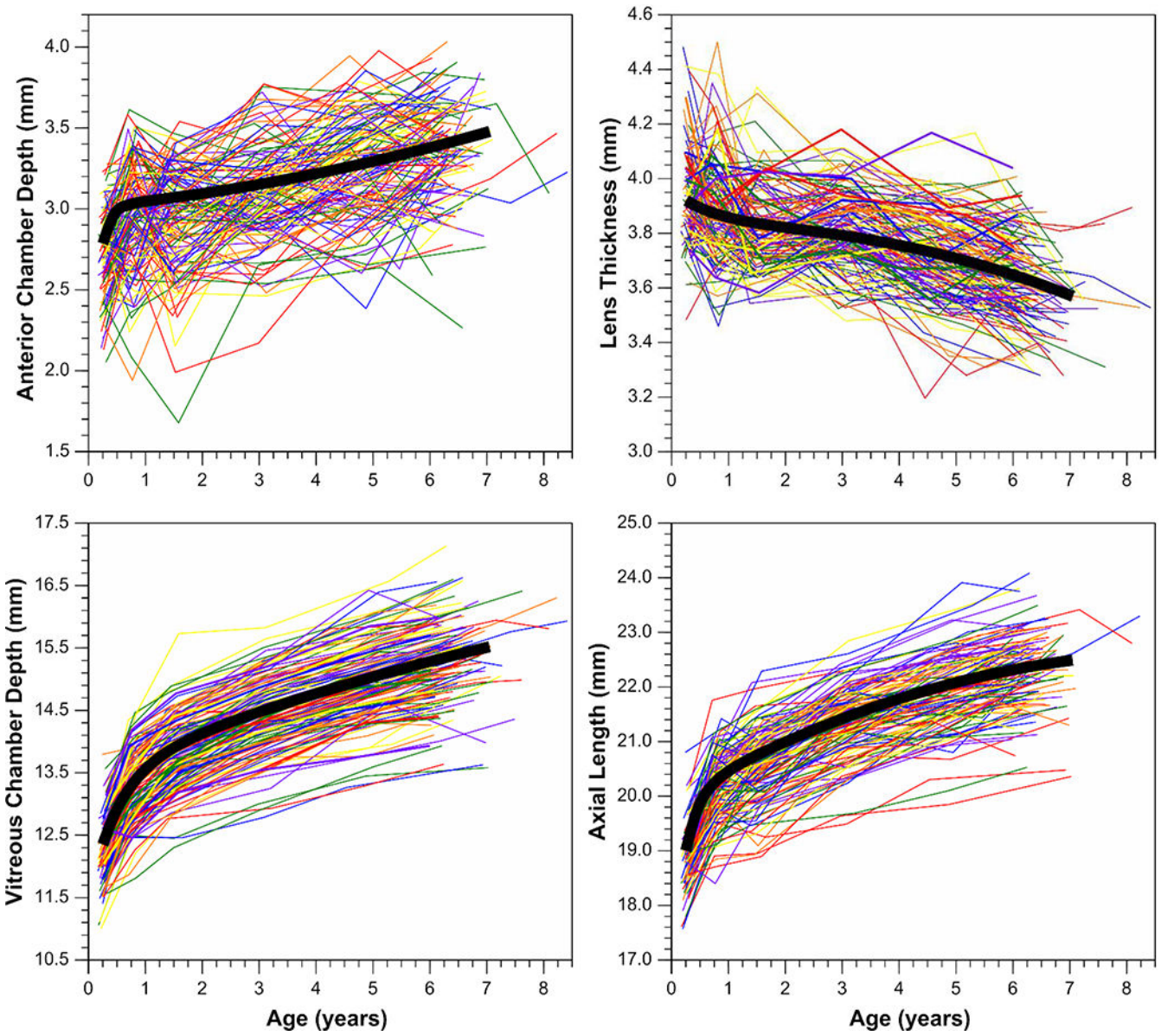

Figure 2.

Growth curves (bold black line) for crystalline lens radii of curvature, refractive power, refractive index, corneal power, and refractive error superimposed over the individual data.

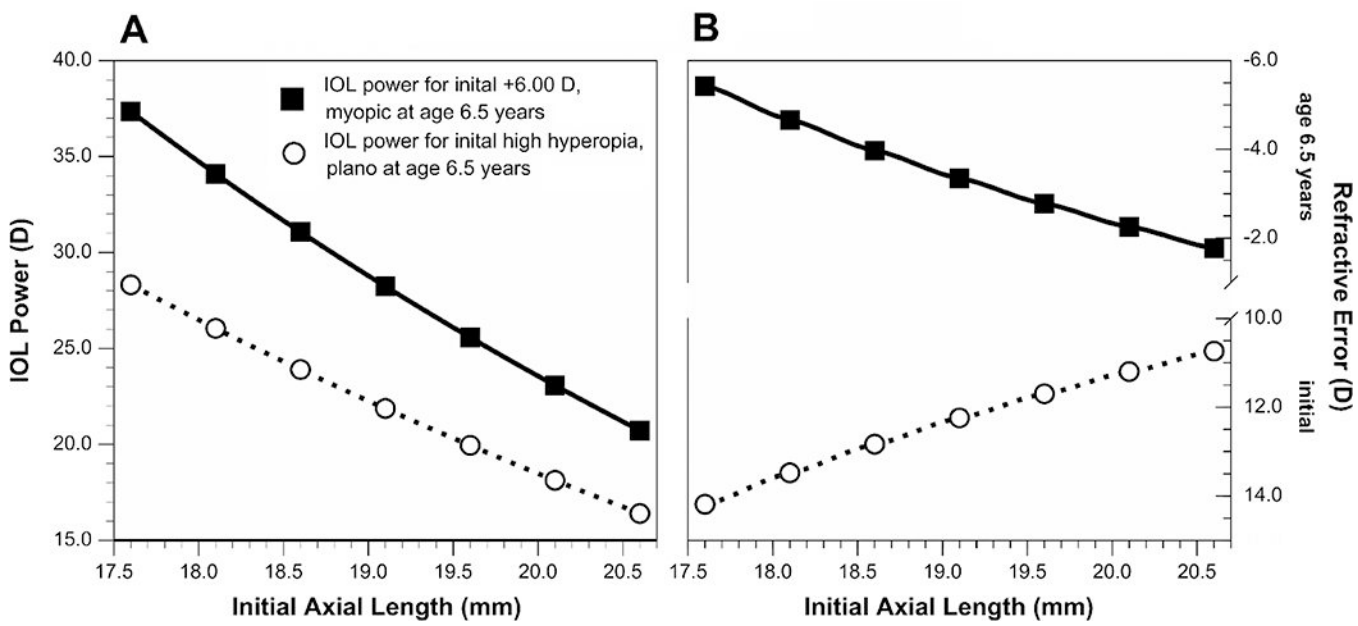

Figure 3.

(A) Intraocular lens (IOL) powers needed to produce a uniform refractive error of +6.00 D at age 3 months (solid line) and IOL powers needed to produce emmetropia at age 6.5 years (dotted line) as a function of initial axial length. IOL powers along the dotted line will produce higher initial post-surgical hyperopia than +6.00 D. **(B, solid line)** Refractive errors predicted at age 6.5 years after implanting IOL powers described by the solid line in panel (A) as a function of initial axial length, i.e., that produced a uniform refractive error of +6.00 D at age 3 months. More myopia at age 6.5 years for initially smaller eyes is the result of effectivity; more diopters of change in refractive error will occur per mm of growth for initially smaller eyes. The dotted line **in (B)** shows the highly hyperopic refractive errors at 3 months predicted to produce emmetropia at age 6.5 years. Higher initial post-surgical hyperopia is required for smaller eyes because of effectivity.

Table 1.

Mean values ± SD for each ocular component by visit. The number of subjects for each measurement and visit is given in parentheses.

Visit	1	2	3	4	5	6
Target Age	0.25 years (3 months)	0.75 years (9 months)	1.5 years (18 months)	3 years	4.5 years	6.5 years
Age ± SD (years)	0.30 ± 0.070 (293)	0.80 ± 0.070 (278)	1.52 ± 0.090 (264)	3.06 ± 0.13 (243)	4.93 ± 0.42 (162)	6.52 ± 0.42 (196)
Refractive Error (SEQ; D)	2.07 ± 1.32 (293)	1.31 ± 1.02 (278)	1.08 ± 0.90 (264)	1.23 ± 0.97 (242)	1.31 ± 1.02 (162)	1.11 ± 1.01 (196)
Keratometer power (D)	43.9 ± 1.54 (289)	42.9 ± 1.48 (272)	42.7 ± 1.53 (259)	42.5 ± 1.41 (241)	42.4 ± 1.36 (156)	42.4 ± 1.33 (196)
Anterior chamber depth (mm)	2.83 ± 0.32 (292)	3.06 ± 0.36 (257)	3.01 ± 0.35 (257)	3.15 ± 0.30 (240)	3.29 ± 0.31 (160)	3.42 ± 0.30 (196)
Lens thickness (mm)	3.91 ± 0.16 (292)	3.87 ± 0.18 (259)	3.83 ± 0.17 (257)	3.81 ± 0.16 (240)	3.70 ± 0.17 (160)	3.60 ± 0.16 (196)
Vitreous chamber depth (mm)	12.45 ± 0.56 (292)	13.35 ± 0.56 (259)	13.87 ± 0.61 (257)	14.46 ± 0.64 (240)	14.98 ± 0.62 (160)	15.38 ± 0.67 (196)
Axial length (mm)	19.19 ± 0.69 (292)	20.29 ± 0.64 (257)	20.71 ± 0.7 (257)	21.42 ± 0.68 (240)	21.96 ± 0.70 (160)	22.39 ± 0.71 (196)
Anterior lens radius (mm)	7.28 ± 0.62 (286)	8.97 ± 0.74 (251)	10.04 ± 0.82 (250)	10.75 ± 0.91 (237)	11.47 ± 1.00 (154)	12.30 ± 1.15 (195)
Posterior lens radius (mm)	4.69 ± 0.30 (286)	5.19 ± 0.35 (251)	5.62 ± 0.46 (250)	5.89 ± 0.45 (237)	6.16 ± 0.44 (154)	6.27 ± 0.46 (195)
Lens power (D)	40.3 ± 2.58 (286)	37.2 ± 2.09 (251)	35.1 ± 2.24 (250)	31.7 ± 1.94 (237)	28.9 ± 1.76 (154)	27.4 ± 1.86 (195)
Lens equivalent index	1.451 ± 0.008 (286)	1.458 ± 0.009 (251)	1.462 ± 0.011 (250)	1.456 ± 0.009 (237)	1.451 ± 0.008 (154)	1.448 ± 0.007 (195)

Table 2.

Baseline values and the average change (± SD) in each ocular component between 3 ± 1 months and 6.5 years ± 6 months of age for subjects with data at each of those two visits. For the sign of the change, the order of subtraction is 6.5 years minus 3 months. The correlation coefficient is also given for the association between values at 3 months and those at 6.5 years of age. Each correlation was significant and positive except for the equivalent index of the crystalline lens.

Ocular component	n	Average Value at 3 months ± SD	Average change ± SD of change	Correlation coefficient
Refractive Error (SEQ; D)	154	2.18 ± 1.30	−1.04 ± 1.21	0.49 (P < .001)
Keratometer power (D)	150	43.9 ± 1.40	−1.52 ± 0.93	0.76 (P < .001)
Anterior chamber depth (mm)	153	2.76 ± 0.27	0.64 ± 0.34	0.24 (P = .003)
Lens thickness (mm)	153	3.93 ± 0.16	−0.32 ± 0.19	0.25 (P = .001)
Vitreous chamber depth (mm)	153	12.3 ± 0.47	3.04 ± 0.56	0.50 (P < .001)
Axial length (mm)	153	18.99 ± 0.54	3.35 ± 0.64	0.44 (P < .001)
Anterior lens radius (mm)	148	7.13 ± 0.53	5.13 ± 1.09	0.25 (P = .002)
Posterior lens radius (mm)	148	4.65 ± 0.31	1.62 ± 0.45	0.40 (P < .001)
Lens power (D)	148	41.2 ± 2.20	−13.6 ± 2.44	0.26 (P = .002)
Lens equivalent index	148	1.452 ± 0.008	−0.0033 ± 0.0099	0.12 (P = .16)

Table 3.

Correlation coefficient matrix for refractive error and ocular component values at 3 months of age. Significant correlations are marked in bold.

	SEQ (D)	K (D)	ACD (mm)	LT (mm)	VCD (mm)	AL (mm)	ALC (mm)	PLC (mm)	CLP (D)
SEQ (D)	1								
K (D)	***−0.21***[b]	1							
ACD (mm)	−0.09	−0.10	1						
LT (mm)	0.00	0.03	***−0.30***[c]	1					
VCD (mm)	***−0.41***[c]	***−0.50***[c]	***0.26***[c]	***−0.31***[c]	1				
AL (mm)	***−0.39***[c]	***−0.46***[c]	***0.61***[c]	***−0.13***[a]	***0.89***[c]	1			
ALC (mm)	0.08	***−0.33***[c]	0.08	***−0.22***[c]	***0.45***[c]	***0.36***[c]	1		
PLC (mm)	−0.05	***−0.15***[a]	***−0.14***[a]	***−0.26***[c]	***0.37***[c]	***0.18***[b]	***0.40***[c]	1	
CLP (D)	0.04	0.01	***−0.40***[c]	***0.24***[c]	***−0.68***[c]	***−0.69***[c]	***−0.30***[c]	***−0.32***[c]	1

[a] $P < .05$;

[b] $P < .01$;

[c] $P < .001$

Table 4.

Growth curves using equations 1–3 where T = (age in years – 0.25). Sex = 0 for males and Sex = 1 for females.

	Exponential plus quadratic equations
Refractive Error (SEQ; D)	$SEQ = (0.494) + (1.66 * e^{-1.75 * T}) + (0.384 * T) - (0.0463 * T^2)$ $R^2 = 0.11$
Keratometer power (K; D)	$K = [42.4 + (0.734 * Sex)] + (1.24 * e^{-4.01 * T}) + (-0.167 * T) + (0.017 * T^2)$ $R^2 = 0.17$
Anterior chamber depth (ACD; mm)	$ACD = [3.06 - (0.088 * Sex)] - (0.236 * e^{-0.679 * T}) + 0.0343 * T) + (0.0049 * T^2)$ $R^2 = 0.29$
Lens thickness (LT; mm)	$LT = [3.79 + (0.031 * Sex)] + (0.111 * e^{-1.21 * T}) + (0.0115 * T) - (0.00688 * T^2)$ $R^2 = 0.28$
Vitreous chamber depth (VCD; mm)	$VCD = [13.7 - (0.286 * Sex)] - (1.23 * e^{-1.95 * T}) + (0.354 * T) - (0.0102 * T^2)$ $R^2 = 0.76$
Axial length (AL; mm)	$AL = [20.3 - (0.346 * Sex)] - (1.09 * e^{-4.18 * T}) + (0.567 * T) - (0.0317 * T^2)$ $R^2 = 0.76$
Anterior lens radius (ALC; mm)	$ALC = [10.4 - (0.292 * Sex)] - (3.14 * e^{-1.65 * T}) + (0.129 * T) + (0.0333 * T^2)$ $R^2 = 0.81$
Posterior lens radius (PLC; mm)	$PLC = [5.74 - (0.182 * Sex)] - ([1.10 + (0.124 * Sex)] * e^{-1.38 * T}) + (0.102 * T)$ $R^2 = 0.67$
Lens power (CLP; D)	$CLP = [37.6 + (0.984 * Sex)] + (2.58 * e^{-3.21 * T}) - (2.81 * T) + (0.170 * T^2)$ $R^2 = 0.84$
	Growth and decay equation
Lens equivalent index (IND)	$IND = 1.445 + [(0.624 * (1 + T)^{2.25})/(100 + (4.3 * (1 + T)^{4.13}))]$ $R^2 = 0.23$