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# Estimating principal plane positions for ocular power calculations in children and adults

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## Abstract

**Purpose:** To develop an age-dependent model to estimate the positions of the ocular and lenticular principal points (*pps*) for use in ocular and axial power calculations.

**Methods:** Based on previously published average data of the ocular biometry and refraction in newborn infants, children and adults the associated *pp* positions, as well as the ocular power $P_{\text{eye}}$ and axial power $P_{\text{ax}}$ were calculated. Next, regressions of the *pp* positions were made as a function of the logarithm of age, which were subsequently used to estimate $P_{\text{eye}}$ and $P_{\text{ax}}$. These regression-based estimates were compared with the $P_{\text{eye}}$ and $P_{\text{ax}}$ values of the original data for validation. Finally, this procedure was repeated using the Atchison myopic eye model to determine the influence of myopia on the regression estimates.

**Results:** In adults, the corneal *pps* almost coincide at *0.058 mm* in front of the cornea. The first lenticular *pp* position relative to the corneal apex is described by $5.809 - 0.697 \cdot exp(-0.211 \cdot Age)$ ($r^2 = 0.963$), and the second lenticular *pp* by $6.026 - 0.684 \cdot exp(-0.232 \cdot Age)$ ($r^2 = 0.954$). The first ocular *pp* position relative to the corneal apex is at $0.293 \cdot exp(-0.232 \cdot Age) - 2.2 \cdot 10^{-3} \cdot Age + 1.723$ ($r^2 = 0.985$) and the second ocular *pp* is located at $0.392 \cdot exp(-0.181 \cdot Age) - 2.4 \cdot 10^{-3} \cdot Age + 2.093$ ($r^2 = 0.985$). Estimates of $P_{\text{eye}}$ and $P_{\text{ax}}$ derived from these regressions led to minor differences from the original values ($0.00 \pm 0.06D$ and $0.00 \pm 0.10D$, respectfully). These errors were not affected by ocular refraction between $-10D$ and $0D$, with errors of $+0.12 \pm 0.00D$ and $-0.02 \pm 0.05D$ for $P_{\text{eye}}$ and $P_{\text{ax}}$, respectfully.

**Conclusion:** The proposed regression models of the *pp* positions are sufficiently accurate to reliably estimate $P_{\text{eye}}$ and $P_{\text{ax}}$. Interestingly, although the adult lens undergoes considerable physiological changes, its *pps* remain immobile with respect to the corneal apex.

## Introduction

Ocular refraction is typically defined by the corrective lens required to make an eye emmetropic. This corresponds with the difference between ocular power $P_{\mathrm{eye}}$, i.e. the combination of the eye's refractive components, and the axial power $P_{\mathrm{ax}}$, the required optical power to achieve emmetropia for a certain axial length. As such, knowledge of $P_{\mathrm{eye}}$ and $P_{\mathrm{ax}}$ may help to better understand refractive development processes, such as emmetropization and myopization. Calculation of these powers is pretty straightforward, provided one knows the ocular biometry, as well as the position of the principal planes (*pp*). These are mathematical planes in or near a thick lens where all refraction appears to take place. Generally, ocular biometry values are readily available through modern clinical equipment, with the notable exception of the crystalline lens shape, which, due to its position deep inside the eye, can only be determined with expensive MRI systems or custom-made equipment. Consequently, many important aspects of the lens biometry cannot be determined accurately, and with it the lenticular and ocular *pp* positions.

To get around this issue, authors sometimes opt to use fixed values for the *pp* positions based an adult eye models (e.g. *1.58 mm* from the corneal apex for the first ocular *pp* in the Navarro model[1]). However, using such fixed values ignores that fact that the ocular biometry undergoes major changes, both during childhood[2] and in adults.[3] Age is therefore a major factor that must be taken into account when developing reliable estimates of $P_{\mathrm{eye}}$ and $P_{\mathrm{ax}}$. To this end, present work intends to develop a model of the *pp* positions within the eye as a function of age, allowing more accurate estimates of ocular and axial powers.

## Methods

To estimate the *pp* positions, this work uses previously published average biometry data provided by Mutti et al.[2] (infants and children) and Atchison.[3] (adults). Both studies include the required values for lens radii and variable (as opposed to fixed) equivalent refractive indices alongside other, more common ocular biometry values. Notable exceptions were the posterior corneal radii and thickness values that were not available for the children's data. Instead, the posterior radii $r_{\mathrm{cp}}$ were estimated using a regression of the anterior radii $r_{\mathrm{ca}}$:

$$r_{\mathrm{cp}} = 0.821 \cdot r_{\mathrm{ca}} \tag{1}$$

derived from a recent dataset[4] of *4,953* Iranian children aged *9.74 ± 1.68* years that contained both the anterior and posterior cornea radii ($r^2 = 0.862$; $p < 0.001$). For corneal thickness the adult value *0.54 mm* was assumed for all ages. Similarly, to avoid inconsistency between the Mutti et al.[2] and Atchison[3] models, the refractive index $n$ of the humours was taken as *1.336* for all ages and *+0.00265* was added to the children's lens indices to retain the same lens power. Once all required parameters were available and compatible in both models the associated *pp* positions were estimated using the equations in Table 1 (see also Figure 1). The *pp* positions of the models were subsequently plotted as a function of $log_{10}(Age)$ and fitted to exponential regressions for use in the calculation of $P_{\mathrm{eye}}$ and $P_{\mathrm{ax}}$ (Table 1). In clinical practice often a direct estimate for the lens power may not be available, however, in which case the Bennett equation[5, 6] may be used.

### *Influence of myopia*

Since it may be expected that the *pp* positions also depend on the degree of myopic refraction $S$, a modified version of the Atchison myopic eye model[7] was used to assess this influence. This model is identical to the one published, except for the model's gradient index in the crystalline lens, which was replaced by the following expression:

$$n_L = 0.000055 \cdot S^2 - 0.000083 \cdot S + 1.4319 \tag{2}$$

This function was derived by determining the lens equivalent refractive indices at which the calculated refractive error matched the model's nominal refractive error, while keeping all other biometric values of the model for that specific refraction. For a refractive range between [*–10D, 0D*] in *2D* increments, this resulted in a coefficient of determination of $r^2 = 0.999$.

**Table 1: Overview of the biometric parameters and calculations used**

| Symbol | Unit | Calculation/ value | Description |
|---|---|---|---|
| $S$ | *D* | Model | Spherical refraction |
| $d_c$ | *mm* | *0.54 mm* | Central corneal thickness |
| $d_a$ | *mm* | Model | Anterior chamber depth (excl. corneal thickness) |
| $d_l$ | *mm* | Model | Lens thickness |
| $d_{ax}$ | *mm* | Model | Axial length |
| $n_{air}$ | / | *1.000* | Refractive index of air |
| $n_c$ | / | *1.376* | Refractive index of the cornea |
| $n$ | / | *1.336* | Refractive index of the ocular humours |
| $n_l$ | / | Model | Refractive index of the lens |
| $r_{ca}$ | *mm* | Model | Anterior corneal radius of curvature |
| $r_{cp}$ | *mm* | Model (adults); $0.821 \cdot r_{ca}$ (children) | Posterior corneal radius of curvature |
| $P_{ca}$ | *D* | $1000 \cdot (n_C - n_{air})/r_{ca}$ | Anterior corneal curvature |
| $P_{cp}$ | *D* | $1000 \cdot (n - n_C)/r_{cp}$ | Posterior corneal curvature |
| $P_c$ | *D* | $P_{ca} + P_{cp} - 0.001 \cdot P_{ca} P_{cp} d_c/n_c$ | Total corneal keratometry |
| $pp_{c1}$ | *mm* | $(n_{air}/n_c) \cdot (d_c P_{cp}/P_c)$ | Position *1st* corneal *pp* from corneal vertex |
| $pp_{c2}$ | *mm* | $d_c - (n/n_c) \cdot (d_c P_{ca}/P_c)$ | Position *2nd* corneal *pp* from corneal vertex |
| $r_{la}$ | *mm* | Model | Anterior lens radius of curvature |
| $r_{lp}$ | *mm* | Model | Posterior lens radius of curvature |
| $P_{la}$ | *D* | $1000 \cdot (n_L - n)/r_{la}$ | Anterior lens power |
| $P_{lp}$ | *D* | $1000 \cdot (n - n_L)/r_{lp}$ | Posterior lens power |
| $P_l$ | *D* | $P_{la} + P_{lp} - 0.001 \cdot P_{la} P_{lp} d_l/n_l$ | Lens power |
| $pp_{l1}$ | *mm* | $d_c + d_a + (n/n_l) \cdot (d_l P_{lp}/P_l)$ | Position *1st* lens *pp* from corneal vertex |
| $pp_{l2}$ | *mm* | $d_c + d_a + d_l - (n/n_l) \cdot (d_l P_{la}/P_l)$ | Position *2nd* lens *pp* from corneal vertex |
| $P_{eye}$ | *D* | $P_c + P_l - 0.001 \cdot P_c P_l \, pp_{l1}/n$ | Whole eye power |
| $pp_{eye1}$ | *mm* | $pp_{c1} + (n_{air}/n) \cdot [(pp_{l1} - pp_{c2}) \cdot P_l/P_{eye}]$ | Position *1st* ocular *pp* from corneal vertex |
| $pp_{eye2}$ | *mm* | $pp_{l2} - (n/n) \cdot [(pp_{l1} - pp_{c2}) \cdot P_c/P_{eye}]$ | Position *2nd* ocular *pp* from corneal vertex |
| $P_{ax}$ | *D* | $1000 \cdot n/(d_{ax} - pp_{eye2} - pp_{c1})$ | Axial power |

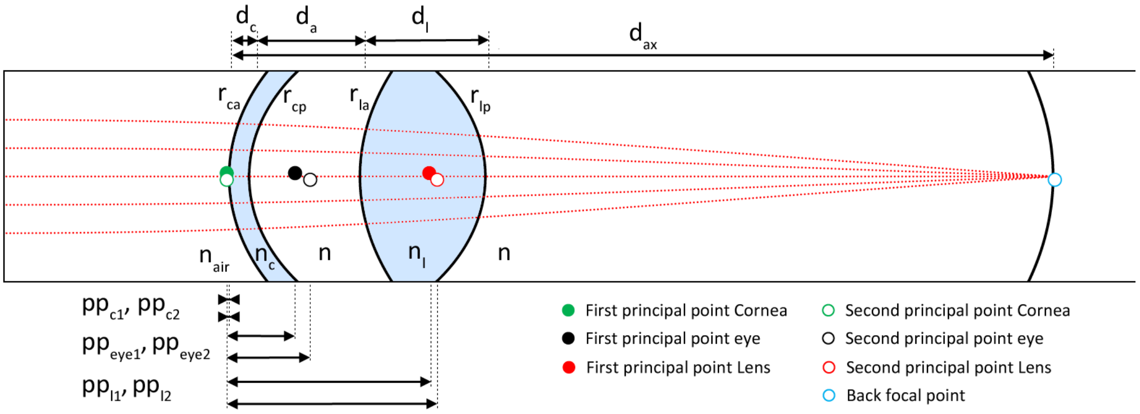

*Figure 1: Definition of the intraocular distances used in the calculations.*

## Results

### *Cornea*

Both corneal *pps* are located at *0.059 mm* and *0.057 mm* in front of the cornea. As they are separated by only *0.002 mm* and shift about *0.004 mm* over the entire lifetime, they can be considered coincident and immobile for any practical purpose.

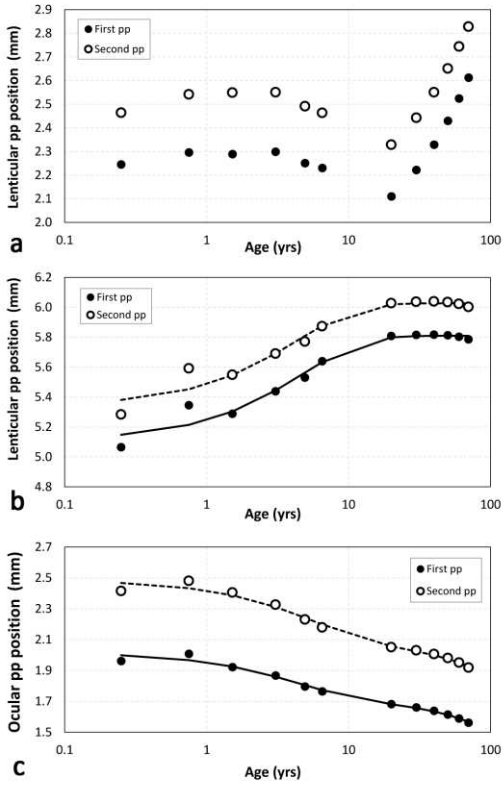

*Figure 2: Position of the first and second principal planes (pp). a. Lenticular pps with respect to the anterior lens surface; b. Lenticular pps with respect to the corneal apex; c. Ocular pps with respect to the corneal apex.*

**Table 2: Position of the corneal, lenticular and ocular principal points with respect to the corneal apex as a function of age (in years)**

| | **Fit (in *mm*)** | **$r^2$ ($p$)** |
|---|---|---|
| $pp_{c1}$ | $-0.059$ | |
| $pp_{c2}$ | $-0.057$ | |
| $pp_{l1}$ | $5.809 - 0.697 \cdot exp(-0.211 \cdot Age)$ | $0.963$ ($<0.001$) |
| $pp_{l2}$ | $6.026 - 0.684 \cdot exp(-0.232 \cdot Age)$ | $0.954$ ($<0.001$) |
| $pp_{eye1}$ | $0.293 \cdot exp(-0.232 \cdot Age) - 2.2 \cdot 10^{-3} \cdot Age + 1.723$ | $0.985$ ($<0.001$) |
| $pp_{eye2}$ | $0.392 \cdot exp(-0.181 \cdot Age) - 2.4 \cdot 10^{-3} \cdot Age + 2.093$ | $0.985$ ($<0.001$) |

$pp_C$: corneal principal point; $pp_L$: lenticular principal point; $pp_{Eye}$: ocular principal point.

### *Lens*

With respect to the anterior lens surface the lenticular principal plane positions, $pp_{l1}$ and $pp_{l2}$, fluctuate over time. First, from birth until three years of age, the planes shift *0.25 mm* towards the retina, followed by a similar shift back towards the cornea until about the age of *12* years. Finally, they move back towards the retina for the rest of life (Figure 2a). Using the anterior cornea as a reference, this pattern simplifies to a logarithmic increase from birth until the age of *19* years, when it stabilizes at a constant value (Figure 2b). This behaviour can be modelled by the equations given in Table 2.

### *Whole eye*

The principal plane positions of the whole eye, $pp_{eye1}$ and $pp_{eye2}$, first shift *0.25 mm* backwards towards the retina between birth and *9* months of age, followed by a continuous motion forward thereafter (Figure 1c). The appropriate fit functions for this behaviour are given in Table 2.

### Validation

To validate the *pp* position estimates in Table 2, the regressions for $pp_{l1}$ and $pp_{eye2}$ were used to estimate $P_{eye}$ and $P_{ax}$. These values remained very close to the intrinsic $P_{eye}$ and $P_{ax}$ power values of the models, with errors of *0.00 ± 0.06D* ($r^2 = 0.999$) and *0.00 ± 0.10D* ($r^2 = 0.999$) for $P_{eye}$ and $P_{ax}$, respectfully (Figure 3a). Meanwhile, to determine the effect of myopia on the accuracy of the estimates, the same calculations were performed for the Atchison myopic eye model for a refractive range from *−10D* to *0D*. Here the errors were *+0.12 ± 0.00D* and *−0.02 ± 0.05D* for $P_{eye}$ and $P_{ax}$, respectfully (Figure 3b).

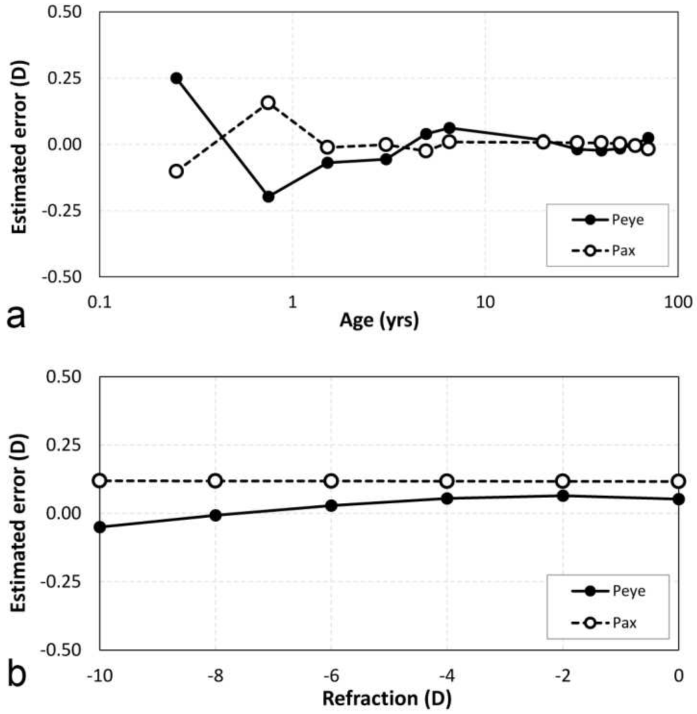

*Figure 3: Error between the estimated and intrinsic model power values for the whole eye power $P_{eye}$ and axial power $P_{ax}$. a. As a function of age; b. as a function of refractive error*

## Discussion

Often the largest restriction to accurately determining the total and axial powers of an eye lies in the fact that the principal point positions are not known. Given that these positions tend to change with age using a fixed value, as is often done in the literature, this may not always lead to appropriate estimates. The results of this work suggest that *pp* positions expressed as regressions of the logarithm of age can be used to accurately estimate the total and axial powers in both children and adults. These values will help to better understand the processes that are at work in refractive development, both during emmetropization and myopization.

One interesting finding was the constant position of the lenticular *pps* with respect to the corneal apex in adults over the age of *20* years. This is especially surprising, given that during this time the lens undergoes numerous physiological changes such as an increase in thickness and surface curvature, while simultaneously experiencing profound changes in its gradient index.[8] The constant *pp* position would suggest that these changes are somehow coordinated, although the purpose of this phenomenon remains as yet unclear.

Lens power equations are fundamentally based on estimates of the *pp* positions. The Bennett equation,[5] for example, assumes that the *pps* are always located at *59.6%* and *64.2%* of the lens thickness, based on the relative powers of the anterior and posterior lens surfaces in the Gullstrand-Emsley eye model.[9] Although in reality this relationship between the lens surfaces will vary between individuals and that these *pp* estimates will gradually shift about *0.2 mm* towards the retina between the ages of *20 – 70* years, the Bennett lens power estimate remains accurate within this age range.[10] In children, on the other hand, the lens shape is very different, requiring different assumptions altogether.

As the ocular *pp* positions change with age, assuming fixed positions (as done e.g. by Bennett[5] using the Gullstrand-Emsley model[9]) may in practice lead to an underestimation $P_{ax}$ of up to *2.5D* in infants or *0.5D* in adults, as well as an incorrect position for $P_{eye}$. The proposed regressions take the age dependency into account, leading to more accurate estimates for $P_{eye}$ and $P_{ax}$.

Finally, it is important to point out that the current work is based on average, rather than raw data, which might have affected the validation of Figure 3. Additional validation of the regressions presented would therefore be recommended, preferably using raw longitudinal data.

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