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Original Article

Nomogram to predict the axial elongation with orthokeratology: A 6-year follow up study

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ABSTRACT

Purpose: To develop and validate a nomogram model for predicting axial elongation in children with myopia undergoing orthokeratology (ortho-k) treatment.
Methods: A cohort of 111 myopic children who received ortho-k between 2014 and 2016 and consistently wore lenses for at least 6 years was analyzed. Right eyes were used as the model group, left eyes as the validation group. Demographic and ocular parameters were collected. A multivariable logistic regression was applied to model group data to construct the nomogram. Discriminative ability was assessed using the concordance index (C-index), calibration plots, and decision curve analysis (DCA). Statistical analysis was conducted in R version 4.2.3, with $p \leq 0.05$ considered significant.
Results: Mean axial elongation in the first year was 0.14 mm (95 % CI: 0.12−0.17 mm); total elongation over six years was 0.83 mm (95 % CI: 0.75−0.91 mm). After adjusting for multicollinearity, age ($\beta = -0.134$, $p < 0.001$), gender ($\beta = -0.226$, $p = 0.011$; males as reference), baseline axial length ($\beta = 0.950$, $p < 0.001$), and first-year axial elongation ($\beta = 1.714$, $p < 0.001$) were independently associated with axial length after six years. The model yielded a C-index of 0.93 (95 % CI: 0.88−0.99) in the model group and 0.80 (95 % CI: 0.80−0.96) in the validation group. DCA showed clinical benefit.
Conclusions: Ortho-k effectively slowed axial elongation over six years. The nomogram reliably predicts whether axial length will exceed 26.0 mm after long-term ortho-k treatment.

Introduction

Myopia, particularly pathological myopia, has become one of the most prevalent global health concerns.[1] Once myopia begins to develop, it is irreversible, and the younger the age of onset, the greater the likelihood of developing complications associated with high myopia later in life. These complications include myopic macular degeneration, retinal detachment, and cataracts. All of these can lead to irreversible vision loss.[2] Studies have shown that axial length (AL) is a stronger predictor of visual impairment or blindness than refractive error. Notably, individuals with an axial length≥26.0 mm have a significantly increased risk, with one in three developing bilateral low vision as they age.[3]

Orthokeratology (ortho-k), which utilizes a reverse-geometry design, temporarily reshape the cornea to improve unaided vision after overnight wear. More importantly, extensive evidence supports the efficacy of ortho-k in controlling axial elongation in children, with over 20 years of clinical application.[4–7] As a result, the use of ortho-k for myopia control has gained widespread adoption. In China alone, >1.5 million patients currently use ortho-k for myopia management.[8] However, the reported effectiveness of ortho-k in controlling axial elongation varies, with reductions ranging from 0.10 mm to 0.20 mm per year.[9] Several studies have sought to predict the efficacy of ortho-k in controlling axial elongation and to provide insights for clinical decision-making. For example, Santodomingo-Rubido et al.[10] identified baseline refractive error, corneal shape, and pupil diameter as factors influencing ortho-k efficacy, while Xu et al.[11] developed and validated a model aimed at predicting 1-year axial elongation. However, these studies generally have short follow-up periods, limiting their utility in predicting the long-term impact of ortho-k on axial length control.

Given the strong association between axial length exceeding 26.0 mm and vision-threatening myopic complications, we selected this threshold as the primary outcome measure. While axial elongation is a continuous process, predicting whether an individual will surpass this clinically significant threshold is particularly relevant for myopia management, as it marks an increased risk of severe ocular pathology. This study therefore focuses on identifying predictive factors for reaching this threshold rather than modeling axial progression as a continuous variable, aiming to provide clinicians with actionable insights for early intervention. Furthermore, we examined the relationship between axial length changes and baseline factors, including age at initial fitting,

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gender, baseline refractive error, and corneal curvature, over an extended follow-up period.

Methods

Study design and patients

This retrospective study adhered to the principles of the Declaration of Helsinki and received ethical approval from the Institutional Review Board/Ethics Committee of Guangzhou Aier Hospital, China. A cohort of 111 myopic children who underwent ortho-k treatment at Guangzhou Aier Hospital between 2014 and 2016 and consistently wore the lenses for a minimum of 6 years was reviewed. At the initiation of ortho-k therapy, written informed consent was obtained from the participants' parents, as all subjects were under 13 years of age. Exclusion criteria included: (1) prior ortho-k treatment; (2) discontinuation of ortho-k use during the study period; (3) pre-existing ocular or systemic conditions, other than ametropia, or a history of ocular surgery; (4) use of additional myopia control strategies, such as atropine; and (5) poor-quality topographic measurements. The right eyes were designated as the model group, while the left eyes served as the validation group.

Data collection and evaluation

Data were collected across several categories, including demographic characteristics, anterior segment measurements, refractive status, axial length, corneal curvature, ortho-k treatment details, and adverse effects. Demographic information consisted of gender and age at the initiation of ortho-k therapy. Refractive error was documented as spherical power and astigmatism, with the spherical equivalent refraction (SER) calculated by adding half of the cylindrical power to the spherical power. Axial length measurements (Zeiss IOL-Master; Zeiss Humphrey Systems, Dublin, CA) were obtained at baseline and annually thereafter. Corneal curvature, including flat keratometric power (Kf) and steep keratometric power (Ks), was assessed using Autorefractor (Topcon KR8900, Japan).

All participants were fitted with four-zone reverse-geometry ortho-k lenses based on the Vision Shaping Treatment (VST) design, which included both standard and toric lens designs. Four VST-based products were used: Euclid (Euclid Systems Corporation, Herndon, VA, USA), Alpha (Alpha Corporation, Japan), Hiline (Nanpeng Hiline Inc., Taiwan), and Lucid lenses (Korea Dream Lens; Lucid Korea, Seoul, Korea). These lenses are not identical; they differ in certain geometric parameters (e.g., optic zone diameter, reverse curve width, and alignment curve design) and are manufactured with different high-Dk materials. Nevertheless, all share a four-zone VST design, and prior studies have reported comparable clinical outcomes in myopia control despite minor topographic variations.[12] Therefore, they were analyzed collectively in this study. Lenses were prescribed following the manufacturer's fitting guidelines, and participants were instructed to wear the lenses nightly for approximately eight consecutive hours, unless otherwise directed. The primary outcomes of the study were the final axial length measurement and whether the axial length exceeded 26.0 mm after 6 years of ortho-k treatment.

Data analysis

In the descriptive analysis, categorical variables were reported as frequencies and percentages, normally distributed continuous variables as means with standard deviations (SD), and non-normally distributed continuous variables as medians with interquartile ranges (IQR). Differences in means, medians, and proportions between the model and validation groups were assessed using *t*-tests, Mann-Whitney U tests, and chi-square tests, respectively. All variables from the model group were included in a multivariable logistic regression analysis, with backward stepwise selection based on the Akaike's Information Criterion (AIC) to develop the final predictive model. Variance inflation factors (VIF) were calculated for each variable to evaluate multicollinearity, with a VIF > 4 indicating the presence of collinearity. A nomogram was developed based on the final predictive model. To evaluate the model's performance in identifying patients whose axial length remained ≤26.0 mm after six years of ortho-k treatment, the concordance index (C-index) was calculated along with its 95 % confidence interval (CI). In this study, the C-index is equivalent to the area under the receiver operating characteristic curve (AUC). Comparisons between individual predictors and the final predictive model were conducted for both the model and validation groups. Although the validation group was derived from a temporally separate cohort at the same clinical center, and not from an independently randomized split, we used this pragmatic approach to reflect real-world clinical timelines. We acknowledge that this may introduce potential correlations between the modeling and validation sets, which could overestimate model performance. To address this limitation, we additionally calculated intraclass correlation coefficients (ICCs; two-way mixed, absolute agreement) between right and left eyes for key model variables (baseline AL, SER, CR) and the primary outcome (6-year AL) to quantify inter-eye dependence. To further mitigate overestimation, we performed calibration and decision curve analysis.

The stability of the predictive model was further assessed in the validation group using receiver operating characteristic (ROC) curves, calibration curves, and decision curve analysis (DCA). The roc.test function in R was used to calculate p-values for C-index comparisons. Calibration curves were generated using bootstrap resampling ($n = 1000$) to evaluate the agreement between the predicted probabilities from the nomogram and the actual outcomes. Decision curve analysis was performed to assess the clinical utility of the predictive model. Unlike traditional performance metrics such as AUC, which measure overall discrimination, DCA evaluates the net benefit of a predictive model across a range of threshold probabilities, providing insight into its usefulness for real-world clinical decision-making. All statistical analyses were conducted using R statistical software version 4.2.3. A P-value ≤ 0.05 was considered statistically significant.

Results

Table 1 presents the demographic characteristics and ocular parameters of the study participants in both the model and validation cohorts. A total of 111 subjects were included in the study, with the right eyes designated as the model group and the left eyes as the validation group. Clinical parameters recorded included baseline SER, flat Kf, Ks, AL, and the change in axial length during the first year and after six years. Since age did not follow a normal distribution, it is reported as the median with IQR, and comparisons between groups were made using the Mann-Whitney U test. For other continuous variables that were normally distributed, data are presented as means with SD, and P-values were calculated using *t*-tests. Statistical analysis showed no significant differences between the two groups. ICCs demonstrated strong inter-eye correlation for axial length (baseline ICC = 0.88; 6-year ICC = 0.86), and moderate-to-high correlation for spherical equivalent refraction (ICC = 0.79) and corneal curvature radius (ICC = 0.82). These results indicate that fellow eyes are not statistically independent. Accordingly, the left-eye analysis is interpreted as a within-subject concordance check rather than an external validation, and this limitation is highlighted in the Discussion. During the first year of ortho-k treatment, the mean increase in axial length was 0.14 mm (95 % CI: 0.12 to 0.17), with a mean increase of 0.15 mm (95 % CI: 0.12 to 0.17) in the right eye and 0.13 mm (95 % CI: 0.10 to 0.16) in the left eye. Over the six-year follow-up period, the total axial length increase was 0.83 mm (95 % CI: 0.75 to 0.91), with the right eye showing an increase of 0.87 mm (95 % CI: 0.76 to 0.98) and the left eye showing an increase of 0.79 mm (95 % CI: 0.68 to 0.91).

Seven variables, including age, gender, baseline SER, baseline Kf, baseline Ks, baseline axial length (BAL), and first-year change in axial length change (fyALc), were incorporated into the multivariate analysis (Table 2). After adjusting for multicollinearity, male gender (OR 4.58,

Table 1
Demographic characteristics and ocular parameters of the study participants in both the model and validation cohorts.

Variables	Median	Model group (OD)	Validation group (OS)	p
Age [IQR]	10 [9, 11]	10 [9, 11]	10 [9, 11]	1
Sex (male %)	82 (36.94)	41 (36.94)	41 (36.94)	1
Sex (female %)	140 (63.06)	70 (63.06)	70 (63.06)	–
Baseline SER, (SD)	−2.82 (1.34)	−2.85 (1.33)	−2.80 (1.36)	0.790
Baseline Kf, (SD)	42.92 (1.24)	42.93 (1.24)	42.90 (1.22)	0.820
Baseline Ks, (SD)	44.16 (1.42)	44.18 (1.51)	44.13 (1.33)	0.793
Baseline AL, (SD)	24.46 (0.71)	24.47 (0.70)	24.44 (0.72)	0.714
First-year change in AL, (SD)	0.14 (0.18)	0.15 (0.17)	0.13 (0.18)	0.319
Six-year AL, (SD)	25.29 (0.83)	25.35 (0.81)	25.24 (0.85)	0.316
Six-year AL>26 mm (%)	48 (21.62)	26 (23.42)	22 (19.82)	0.625

Table 2
Logistic regression and classification predictive model results for AL exceeding 26.0 mm after 6 years of ortho-k treatment.

	Multivariable logistic regression		Classification predictive model	
	OR (95 %CI)[#]	P	OR (95 %CI)[#]	P
Age	0.59 (0.32 to 0.99)	0.060	0.59 (0.33 to 0.99)	0.057
Sex (male control)				
Female	0.22 (0.05 to 0.86)	0.04	0.22 (0.05 to 0.85)	0.037
Baseline AL	1.56 (1.26 to 2.03)	<0.001	1.55 (1.31 to 1.96)	<0.001
First-year change in AL	1.11 (1.06 to 1.18)	<0.001	1.11 (1.06 to 1.17)	<0.001
Baseline SER	1.0 (0.46 to 2.22)	0.991	–	–
Baseline Kave*	1.01 (0.48 to 2.10)	0.971	–	–

* Due to multicollinearity (VIF > 4), baseline Kf and baseline Ks were converted to baseline average keratometry (Kave) and re-included in the analysis.
[#] For each 1/10 unit increase in baseline axial length, each 1/100 unit increase in first-year change in axial length change, and each 1 unit increase in the other variables.

95 % CI: 1.16 to 22.04, $P = 0.039$), greater baseline axial length (OR 1.56, 95 % CI: 1.27 to 2.03, $P < 0.001$), and greater fyALc (OR 1.11, 95 % CI: 1.06 to 1.18, $P < 0.001$) were found to be independently associated with axial length exceeding 26.0 mm after six years of ortho-k treatment. Following bidirectional stepwise selection based on the AIC, the variables included in the final classification predictive model were age, gender, baseline axial length, and fyALc. Although the association between age and axial length exceeding 26.0 mm after six years was not statistically significant ($P > 0.05$), age was still retained in the predictive model. The formula for calculating the predicted probability (P) is as follows: Logit(p) = −105.81 - 0.53 × age - 1.52 × gender (female = 1, male = 0) + 4.40 × BAL + 10.32 × fyALc.

$$P = \frac{e^{\mathrm{Logit}(p)}}{1 + E^{\mathrm{Logit}(p)}}$$

The final predictive model results are presented in a nomogram (Fig. 1). The nomogram predicts the probability of axial length exceeding 26.0 mm after six years of ortho-k treatment by assigning weighted scores to each of the relevant factors. To apply the nomogram in practice, the clinician identifies the patient's value for each predictor (e.g., baseline AL, SER, K values) on the corresponding axis, draws a vertical line upward to the "Points" scale to obtain the score, and then sums the individual scores across all predictors. The total score is then projected downward to the probability axis, yielding the estimated risk of axial length >26.0 mm. For example, a child with a baseline AL of 24.5 mm, SER of −3.00 D, and flat K of 42.0 D would obtain approximately 130 total points, corresponding to an estimated 85 % probability of maintaining AL ≤26.0 mm after 6 years.

We used the C-index (equivalent to the area under the ROC curve [AUC]) to evaluate the model's ability to identify whether axial length exceeds 26.0 mm after six years of ortho-k treatment (Fig. 2). The C-index for the nomogram in the model and validation groups was 0.93 (95 % CI: 0.88 to 0.99) and 0.88 (95 % CI: 0.80 to 0.96), respectively. In both groups, the AUC of the predictive model was significantly higher than that of any individual predictor. The calibration curves were generally close to the ideal curve (Fig. 3). However, in both the model and validation groups, the calibration curves slightly deviated from the ideal line when the predicted probability ranged between 0.10 and 0.40, with the actual probability of axial length exceeding 26.0 mm being slightly lower than the predicted probability. Similarly, a slight deviation was observed when the predicted probability was between 0.40 and 0.60, with the actual probability being slightly higher than predicted. The DCA (Fig. 4) demonstrated that the predictive model provides a net benefit over default strategies (treating all or none) across a range of threshold probabilities. This suggests that the model can assist clinicians in stratifying myopia progression risk and making informed decisions regarding ortho-k treatment. Using baseline axial length alone to predict axial length control after six years of ortho-k treatment demonstrated clinical utility, whereas age or first-year change in axial length change alone did not.

Discussion

Consistent with previous studies, the findings of this retrospective study, with a long-term follow-up period of up to 6 years, further confirm that ortho-k is effective in slowing the progression of axial length.[13–15] Among patients who wore ortho-k for over 6 years, less than half exhibited axial length exceeding 26.0 mm,which is closely associated with myopia-related blinding ocular diseases.[3] However, it is important to acknowledge that selecting 26.0 mm as a cutoff criterion is somewhat arbitrary. Myopia-related complications, such as myopic maculopathy and visual impairment, can occur even at much lower degrees of myopia and shorter axial lengths. This highlights the complex interplay between retinal, optical, and environmental factors involved in the pathogenesis of

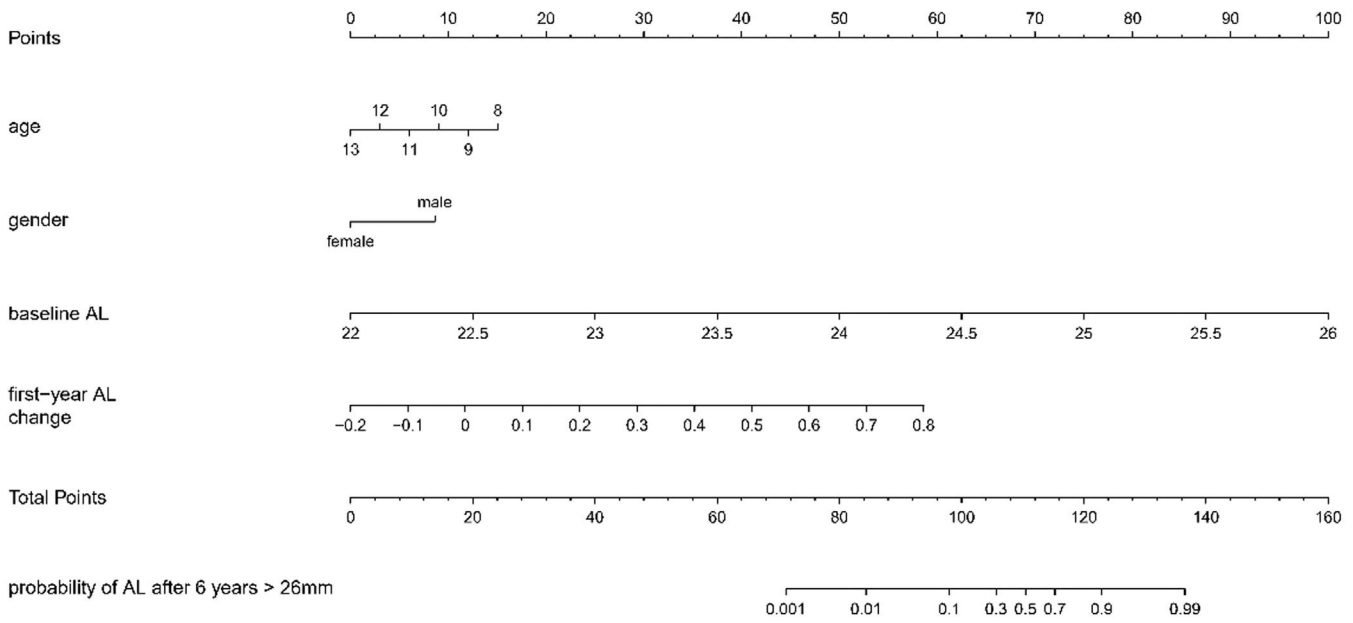

Fig. 1. Nomogram to predict the axial elongation with ortho-k.

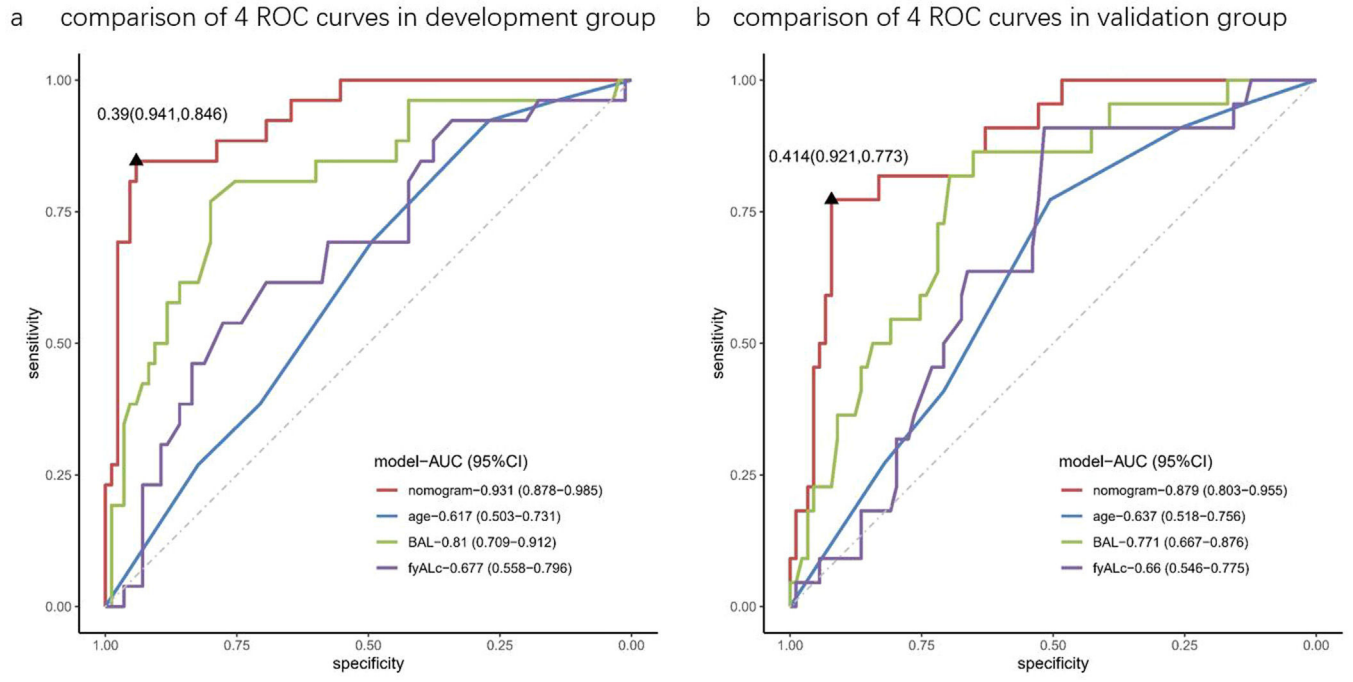

Fig. 2. Comparison of 4 ROC curves in both groups.

myopia and its related complications.[16,17] In addition, though myopia progression is a complex and multifactorial clinical phenomenon, this study found that it was practical to predict long-term axial length with baseline age, gender, baseline axial length and the first-year axial length change. To the best of our knowledge, the present study is the first report on developing a nomogram to predict and verify the axial length with ortho-k for >6 years. To facilitate clinical application of the developed nomogram, clinicians can follow these simple instructions: first, determine the patient's baseline age, gender, baseline axial length, and measure the axial length change after one year of orthokeratology treatment. Then, align these parameters with the corresponding scales on the nomogram to estimate the probability of axial length exceeding 26 mm after six years. This practical approach can help clinicians predict long-term treatment outcomes and personalize myopia management plans accordingly. In addition, we situate our model within the current predictive landscape. Recent work such as Liu et al., has summarized AI-driven approaches for myopia control, underscoring the value of individualized risk stratification based on multimodal data.[18] Likewise, Hu et al. 2025 developed a prediction model for young Chinese children that focuses on early myopia risk using biometric and perinatal factors and demonstrated solid internal/external validity.[19] Unlike these general or onset-oriented frameworks, our nomogram is explicitly derived from a cohort of children consistently wearing ortho-k and targets 6-year axial-length outcomes, thereby providing treatment-specific, long-horizon risk estimates that are

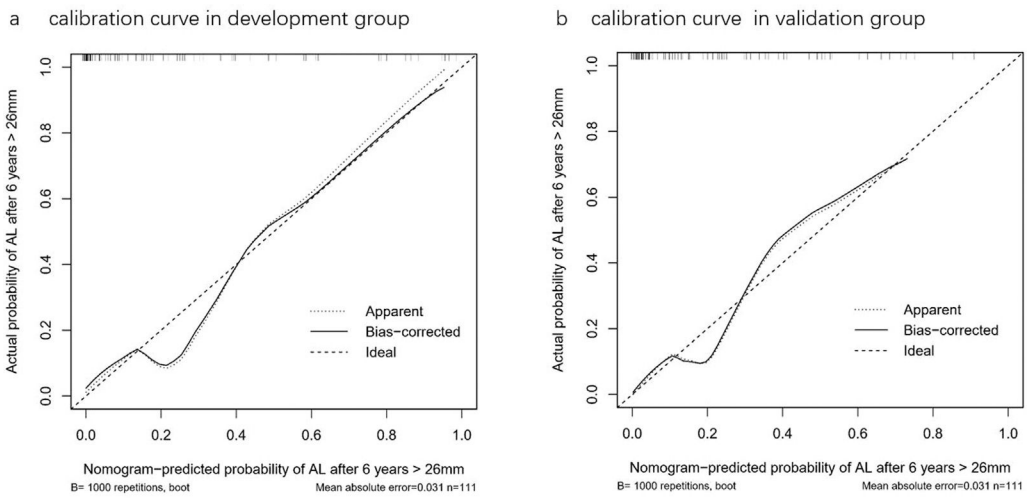

Fig. 3. The calibration curves in both groups.

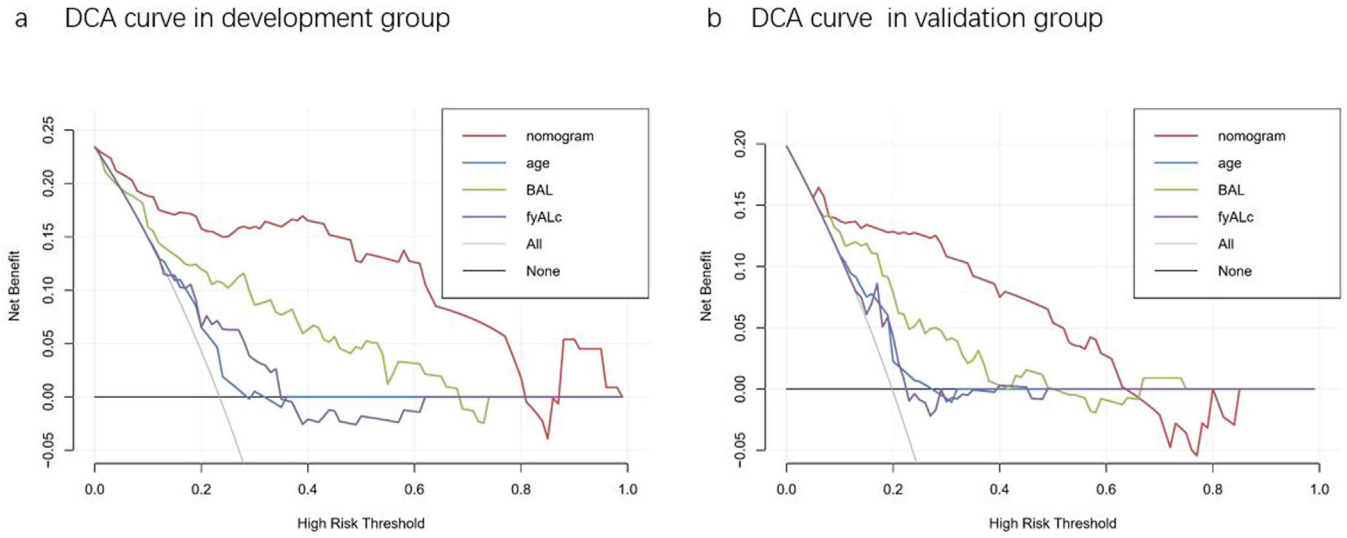

Fig. 4. The DCA curves in both groups.

directly actionable in ortho-k clinical decision-making. These distinctions also provide context for interpreting the relative contributions of individual predictors in our model, as discussed below.

Age alone did not significantly predict whether axial length would exceed 26.0 mm after six years; however, it remained in the model due to its interaction with other factors. In this nomogram, younger baseline age was associated with higher predicted risk scores, indicating a greater likelihood of excessive axial elongation. This aligns with previous studies suggesting that early-onset myopia is associated with a faster rate of axial elongation, likely due to the prolonged duration of active eye growth.[20] Indeed, longitudinal evidence has clearly demonstrated that earlier onset of myopia significantly increases the likelihood of developing high myopia in adulthood.[21,22] Consequently, younger children may be more susceptible to rapid myopic progression, increasing their risk of developing high myopia over time. Moreover, these findings indicate that while age alone was not a definitive predictor of axial length exceeding 26.0 mm, its combined effect with baseline axial length and early treatment response appeared to influence long-term outcomes. Although formal interaction terms were not included in the statistical model, these factors showed correlated predictive behavior and should be further explored in future analyses. Including age in the nomogram enhances its predictive capacity, allowing for a more individualized approach that accounts for the multifactorial nature of myopia progression.

Gender emerged as the second most influential factor in our predictive model for axial length progression. Longitudinal studies suggest that females typically experience faster myopic progression than males, especially during school age. However, our model indicates that when using ortho-k, this trend may differ. The faster progression in females has been associated with a combination of increased near work activities, such as reading and writing, shorter reading distances, and potential hereditary influences, which together predispose them to myopia.[23] Interestingly, our prediction model suggests that females benefit more from ortho-k compared to males, consistent with findings from Santodomingo-Rubido et al., who reported smaller increases in axial length among female ortho-k users.[10] This difference may be attributed to variations in corneal biomechanics or anatomical factors, which could enhance the efficacy of ortho-k in controlling axial elongation.[24]

In this study, baseline axial length proved to be a critical predictor for long-term AL outcomes following ortho-k intervention. The DCA of our predictive model demonstrated that baseline axial length had

substantial clinical utility in predicting axial length control over a 6-year period, whereas age alone or the first-year axial length change did not show similar predictive power. This finding is consistent with previous researches.[25,26] Chen et al. found that baseline axial length could be a significant factor in determining the trajectory of myopic progression in children undergoing ortho-k treatment.[27] Their study highlighted that children with longer baseline axial length were more likely to experience greater axial elongation over time, even when using ortho-k. This is likely because a longer initial axial length may indicate a higher intrinsic growth potential of the eye, making it more prone to further elongation. As such, baseline axial length serves not only as an indicator of the current myopic state but also as a predictive marker for future progression. The incorporation of baseline axial length into predictive models allows for a more individualized approach to myopia management. For example, our study suggests that patients with longer baseline axial length might benefit from more frequent follow-up visits and potentially earlier or more intensive interventions to better control the risk of significant axial elongation. This is particularly important because axial length exceeding 26.0 mm is associated with a higher risk of myopia-related complications, such as retinal detachment and myopic maculopathy.[3]

In our predictive model, the first-year change in axial length proved to be a significant indicator of long-term outcomes in children undergoing ortho-k treatment. Studies have shown that factors like pupil diameter, corneal curvature, and baseline refractive error can impact the control of axial elongation.[10,27] Additionally, changes observed in corneal topography during ortho-k have been used as predictors of treatment efficacy.[11] However, we posit that the effects of these individual parameters ultimately converge in the observed first-year change in axial length. This change reflects the cumulative response of the eye to ortho-k during a critical adaptation period, effectively summarizing the impact of baseline ocular characteristics and the eye's biomechanical response to corneal reshaping. In our study, baseline refractive error and corneal curvature were excluded from the model due to multicollinearity, indicating that their predictive value overlaps with that of the first-year axial length change. Thus, the first year of axial length change offers a practical measure of how well a patient responds to ortho-k treatment. By focusing on the first-year axial length change, our model provides a more streamlined approach that encapsulates the combined effects of various baseline factors, making it a valuable tool for predicting long-term myopia control with ortho-k.

This study has several limitations. First, although modeling axial elongation as a continuous variable may offer additional insights, our primary goal was to identify children at high risk of reaching the clinically significant threshold of 26.0 mm. Future studies with larger datasets and alternative modeling approaches may better characterize axial elongation trajectories. Second, although internal validation was performed using the contralateral eye cohort, the absence of a fully independent dataset or randomized data splitting may have introduced correlation between groups, potentially inflating model performance. To address this issue, we assessed the correlation between right and left eyes using the ICC, which showed only moderate correlation for key baseline and outcome variables, supporting the pragmatic use of contralateral eyes as a validation cohort. Nevertheless, this approach cannot replace true external validation. Calibration and decision curve analysis supported the model's stability, but validation using independent multi-center cohorts remains essential to confirm the generalizability of the nomogram. Third, all participants were recruited from a single clinical center in Guangzhou, China, and were relatively homogeneous in ethnicity and sociodemographic background. This may restrict the applicability of the model to other populations with different ethnic or socioeconomic characteristics. In addition, some clinically relevant predictors, such as parental myopia and the axial length-to-corneal radius (AL/CR) ratio, were not included because of incomplete data and concerns about overfitting with the modest sample size. These variables should be incorporated in larger and more diverse cohorts to further improve predictive accuracy. Finally, patient compliance — an important factor influencing the efficacy of myopia control interventions—was not quantitatively assessed and should be considered in future studies.[28]

In conclusion, this study presents a clinically practical and user-friendly predictive model that aids clinicians in identifying children at higher risk of excessive axial elongation, allowing for more personalized myopia management strategies. By providing clearer expectations of treatment outcomes, this model also helps improve parental adherence to ortho-k therapy. The findings reinforce the importance of early intervention and individualized monitoring in myopia control. Future research should focus on refining the model through large-scale, multicenter studies and leveraging machine learning techniques to enhance its predictive accuracy.[29] Such advancements would facilitate broader clinical validation, ensuring its effectiveness across diverse populations and healthcare settings.

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Conflicts of interest

No conflict of interest exists.

Acknowledgment

None.

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