Received: 8 March 2024 | Accepted: 7 June 2024

DOI: 10.1111/opo.13353

OPO THE COLLEGE OF OPTOMETRISTS

ORIGINAL ARTICLE

Description of a new method to calculate the equator of the crystalline lens using AS-OCT images: Accuracy in non-dilated measurements

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Abstract

Objective: To establish a methodology for objectively estimating the Lens Equatorial Plane (LEP) from clinical images, comparing LEP with dilated versus non-dilated pupils.

Methods: A cohort of 91 eyes from 60 patients undergoing preoperative assessments for cataract surgery was evaluated. Anterior Segment Optical Coherence Tomography (AS-OCT) images were analysed under conditions of pharmacologically induced pupil dilation versus a non-dilated pupil. Geometrical parameters, including LEP, intersection diameter (ID), lens thickness (LT), anterior and posterior lens thickness were automatically calculated by applying standard image processing techniques to clinical AS-OCT images.

Results: Significant differences in lens parameters, including LEP, were observed between dilated and non-dilated conditions (all $p < 0.001$). A strong linear correlation was found across all geometrical variables under both conditions (r[LEP] = 0.64, r[ID] = 0.78, r[LT] = 0.99, all $p < 0.001$); enabling reliable correction of these differences.

Conclusion: The study introduces an objective methodology for LEP calculation, emphasising the need to consider the eye's physiological state during preoperative measurements. Incorporating LEP into future intraocular lens (IOL) power calculation formulas and replacing the habitual effective lens position may potentially improve the accuracy of IOL power estimation and thus postoperative visual outcomes.

KEYWORDS
cataract surgery, crystalline lens, lens equatorial plane, mydriasis, pupil size

INTRODUCTION

The objective of cataract surgery—the most common ocular surgical procedure worldwide—has evolved from simply removing the opacified lens to seeking an optimal refractive outcome.[1] An accurate intraocular lens (IOL) position prediction, which can only be estimated at present, is critical for achieving this ambitious goal.[2] The Lens Equatorial Plane (LEP), a term describing the distance between the anterior cornea and the crystalline lens equatorial plane, has been found to be a good predictor for the actual lens position—that is, the final postoperative position of the IOL.[3] Hence, understanding and accurately predicting the IOL position is essential for reducing variability and surprising post-operative refractive errors.[4]

Recent studies, including those by Martinez-Enriquez et al.[5] and Yoo et al.[6] have highlighted the importance of three-dimensional (3D) imaging techniques, such as

Anterior Segment Optical Coherence Tomography (AS-OCT), in defining new predictive parameters for the effective lens position. The postoperative IOL position has a major influence on the final refractive error, and thus its prediction is crucial when calculating the IOL power.[7,8] Hence, the geometry of the crystalline lens, and likely the LEP, may become relevant parameters in future methods for calculating the IOL power.[9,10] However, the LEP is not clinically accessible from the majority of current commercial OCTs.

In typical preoperative assessments for cataract surgery, dilation of the pupil is common practice. Evaluation with mydriasis is indispensable, as it provides information on the range of pupil dilation and an extensive view of the crystalline lens and other internal structures of the eye, thus allowing the practitioner to anticipate possible intraoperative complications.

Models of lens geometry may differ with a dilated versus non-dilated pupil due to differences in visibility of the lens. Pupil dilation offers a broader view of the lens, which can lead to a more precise estimation of its geometry. Nonetheless, there might be slight changes when compared with the natural state of the lens, that is, under physiological and photopic conditions without exposure to any pharmacological agents. Therefore, understanding the differences in the crystalline LEP measurements with both a natural (non-dilated) photopic pupil and pharmacologically induced mydriasis is relevant. Such comparative studies could bridge the gap between preoperative lens assessments and the real-time scenarios encountered during surgery, leading to improved models of the lens and a better understanding of postoperative IOL positioning.

The aim of this paper is to locate objectively the equatorial plane of the crystalline lens from clinical AS-OCT images with both a dilated and non-dilated pupil, and evaluate the differences in the LEP. By obtaining LEP measurements under both dilated and non-dilated conditions, we aim to verify the robustness of the model, since small pupil sizes are common in older cataract patients and preoperative biometry is frequently performed prior to dilation. Additionally, improving understanding of the LEP can contribute to higher accuracy in IOL power calculations, and thus optimise the refractive results in cataract surgery.

Key points

- An automated method was developed using clinical images to determine the position of the lens equatorial plane and other geometric parameters, thereby improving the understanding of lens anatomy.
- The parameters outlined are not available in the built-in software of most anterior segment optical coherence tomography systems.
- Significant differences in lens parameters, including the lens equatorial plane, were observed between dilated and non-dilated pupils, which emphasises the need to consider the eye's physiological state during preoperative measurements.

METHODOLOGY

Data collection

This study was approved by the Ethics Committee for Clinical Research of Aragon (CI PI23-629) and adhered to the tenets of the Declaration of Helsinki. Data were collected at the Department of Ophthalmology, Hospital Universitario Nuestra Señora de Gracia in Zaragoza, Spain. A cohort of 91 eyes (60 patients) were evaluated, 73.3 ± 11.2 years old (mean ± SD), 62% female and 38% male, all of whom were prospective candidates for cataract surgery. AS-OCT images were obtained using the Heidelberg Engineering ANTERION OCT Metrics App (heidelbergengineering.com). Images were taken in the same sequence, both without dilation (first image) and then following pharmacologically induced mydriasis (second image). The second image was taken 20–30 mins after phenylephrine 100 mg/mL and tropicamide 10 mg/mL drops had been instilled into the eye.

Data analysis

Only AS-OCT images corresponding to the horizontal meridian were exported for further analysis. This corresponded to a total of 182 images (i.e., 91 eyes under dilated and non-dilated conditions). The images had a fixed size (5783 × 8467 pixels) corresponding to an approximate vertical and horizontal resolution of 2.4 and 2.3 μm/pixel, respectively, estimated using the scale provided by the manufacturer.

Each image was analysed individually using an objective methodology. The first step involved automatically selecting the region of interest (ROI) (Figure 1a), with fixed dimensions of 3600 × 4760 pixels. The ROI selection facilitated image segmentation by eliminating unnecessary areas. Once the ROI was selected, the next step was edge detection (Figure 1b). In this stage, the anterior and posterior cornea and lens edges were located automatically using the Canny edge detection method, widely used for image processing in ophthalmology.[11] Subsequently, the segmented anterior and posterior lens borders were fitted to a second-degree polynomial function (Figure 1c), consistent with the literature.[12] Although the use of conic curves to model the corneal surface is widespread,[13] this model was chosen for its simplicity and good performance, providing small fitting errors. Furthermore, a second-degree polynomial is more reliable for extrapolation when compared with

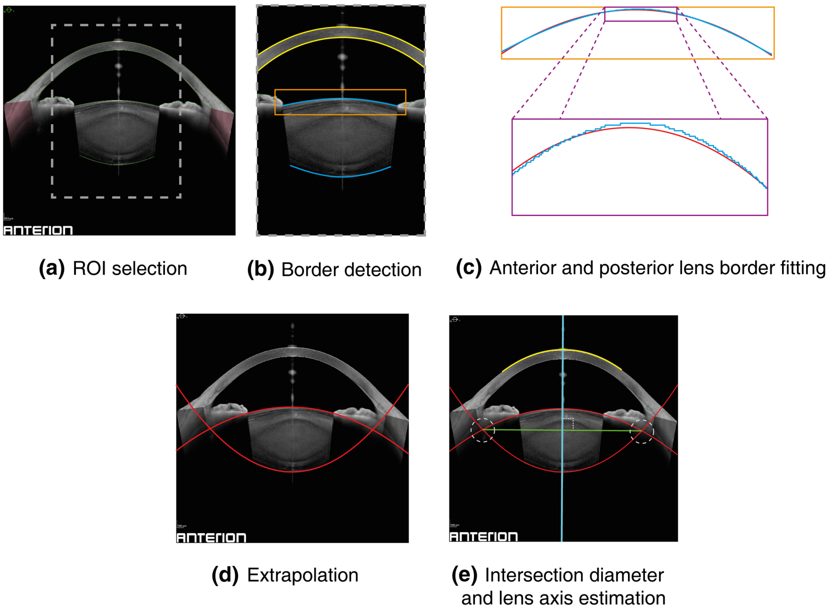

FIGURE 1 The main steps performed to obtain the lens equatorial plane from Anterior Segment Optical Coherence Tomography (AS-OCT) images automatically. (a) Region of Interest (ROI) selection to facilitate segmentation. (b) Border detection to identify the anterior and posterior borders of the cornea and the lens. The yellow and blue lines represent the edges of the cornea and lens, respectively. (c) Second-degree polynomial fitting of the anterior and posterior lens borders. The orange rectangle in (b) shows the anterior lens area to demonstrate fitting of the anterior lens border. The purple rectangle in (c) is zoomed in where the blue and red lines represent the raw and the fitted anterior lens edge, respectively. (d) After fitting (in red), the anterior and posterior lens edges are extrapolated to areas occluded by the iris. (e) Calculation of the intersection points between the anterior and posterior lens borders which indicate the equatorial plane, with corresponding estimation of the lens intersection diameter (in green) and lens axis (in cyan). This method was applied for all the eyes for both a dilated and non-dilated pupil.

more complex models, as it is less prone to overfitting and oscillation, thus ensuring stable and robust predictions near the edges of the range of data. The Root Mean Square Error (RMSE) was the metric chosen for error estimation of the fitting process. The RMSE is calculated by taking the square root of the mean of the squared errors, where each error is the difference between the fitting and observed values (i.e., the lens borders determined by segmentation). In the present analysis, the RMSE was normalised to express it as a percentage, ranging from 0.01% to 1.89%.

The lens border fitting process facilitated the next step, which involved extrapolating the anterior and posterior lens edges in the areas occluded by the iris (Figure 1d). Finally, the intersection points between the anterior and posterior lens borders—necessary to determine the equatorial plane position—were identified (Figure 1e). Once the equatorial plane was located, the lens axis was calculated as the perpendicular to the equatorial plane crossing the crystalline lens apex (Figure 1e).

Finally, the geometric parameters defined in Figure 2 were calculated. These included: the lens equatorial plane (LEP), defined as the distance from the corneal apex to the lens equatorial plane; the intersection diameter (ID), defined as the distance between the intercepts of the anterior and posterior surfaces of the lens; the lens thickness (LT), defined as the maximum axial distance from the anterior to the posterior lens borders; the anterior lens thickness (ALT), defined as the maximum distance from the anterior lens to the lens equatorial plane and the posterior lens thickness

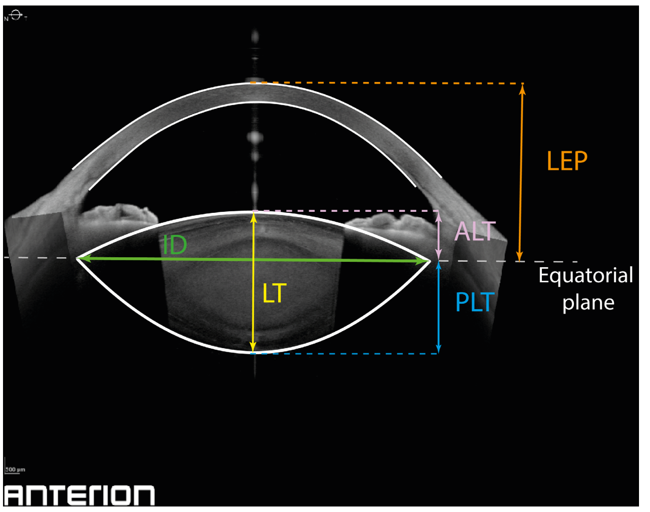

FIGURE 2 Schematic representation of the geometric parameters calculated: anterior lens thickness (ALT), intersection diameter (ID), lens equatorial plane (LEP), lens thickness (LT), and posterior lens thickness (PLT).

(PLT), defined as the maximum distance from the posterior lens to the lens equatorial plane. The same definitions applied to images obtained through dilated and non-dilated pupils. These parameters were calculated along the lens axis, perpendicular to the equatorial plane.

All calculations were performed under dilated and non-dilated conditions. Subsequently, statistical analysis was performed on the parameters described under both situations.

Statistical analysis

Statistical analysis was performed using SPSS statistical software (ibm.com). To compare the parameters described in Figure 2 under the two conditions of interest, namely a dilated or non-dilated pupil, a mixed model univariate analysis of variance (ANOVA) with one fixed factor (dilation or non-dilation) and one random factor (right eye or left eye) was performed. Shapiro–Wilk test, Mauchly's test of sphericity and Levene's test indicated that the assumptions of normality, sphericity and homogeneity of variances, respectively, had not been violated. The level of significance was established at 0.05. The random factor did not interact with the other variables (for all variables $p > 0.05$); therefore, the right and left eyes were treated as indistinguishable.

Furthermore, the Pearson correlation coefficient was calculated to assess the relationship between these parameters with a dilated versus non-dilated pupil. Additionally, for parameters deemed more clinically significant, that is, ID and the LEP, Bland–Altman plots were generated to provide a better understanding of their agreement under the different conditions.

RESULTS

Estimation of the LEP and related parameters from clinically available AS-OCT images is achievable with both a dilated and non-dilated pupil, as demonstrated in Figure 3. Statistical analysis of the geometrical parameters under evaluation (Table 1) revealed significant differences when comparing the two conditions. However, due to the strong linear correlation found across all the geometrical variables determined here (Table 1), these differences were correctable. Notably, a mean difference of 0.32 and 0.18 mm between dilated and non-dilated pupils was observed for the ID and LEP, respectively (Figure 4). The clinical relevance of the ID and LEP warrants further examination, with Figure 5 depicting the correlation between these parameters with both a dilated and non-dilated pupil, along with the corresponding linear equations for estimating ID and LEP under dilated conditions from data acquired in non-dilated conditions.

DISCUSSION

This study sought to establish a methodology for estimating objectively the LEP from AS-OCT images obtained from a commercial device and to compare the values obtained through a dilated and non-dilated pupil. By enhancing our understanding of the LEP, this study aimed to contribute to the ongoing efforts to improve the outcomes of cataract surgery and consequently, the post-surgical quality of vision. The presented methodology, which was completely automated, relied on the location of the equatorial plane (green line in Figure 1e), from which the LEP and other geometrical parameters were determined, as depicted in Figure 2. The position of the equatorial plane appears to coincide with the Intracrystalline Interphase Point (ICIP).[14] The ICIP represents an anatomical variable of the lens, corresponding to the interface between the cortical-epinuclear complex and the crystalline nucleus. Castro et al. found a strong correlation between this preoperative parameter and the final actual lens position.[14] These recent findings on the actual lens position have drawn great interest in determining the location of the LEP accurately and objectively.[3,10]

In the current work, the same automated methodology was applied for 91 eyes in conditions of a natural (non-dilated) pupil versus pharmacologically induced mydriasis. When comparing the two conditions, the ID measured under mydriasis can be considered a better approximation of the actual diameter of the lens. Visibility of the crystalline

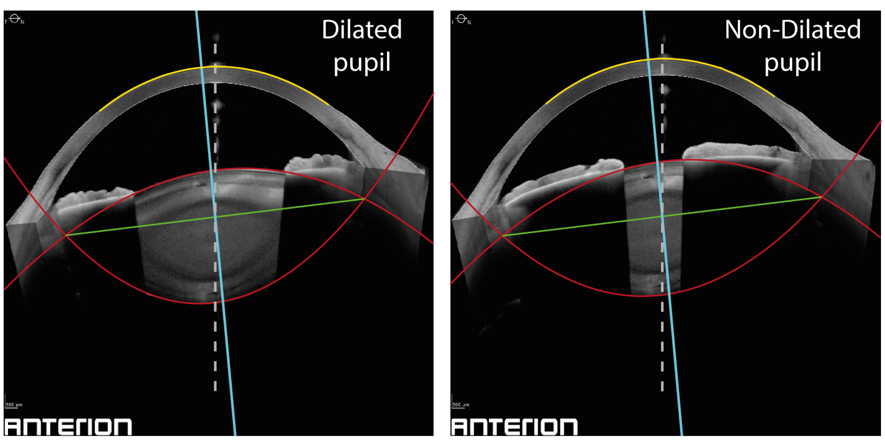

FIGURE 3 Example of the methodology used for the same participant with a dilated pupil (left) and a non-dilated pupil (right). Blue line: Lens axis (perpendicular to the equatorial plane). Grey-dashed line: vertical axis.

lens was enhanced under mydriasis and, consequently, the number of data points available to fit the lens' anterior and posterior surfaces was higher (Figure 1c). Increasing the number of data points improved the reliability of the extrapolation process (Figure 1d), which leads to a more accurate estimation of the equatorial plane (Figure 1e). Significantly differences in lens parameters, including the LEP, were observed between the two states (Table 1), emphasising the necessity of understanding these variations to achieve optimal surgical outcomes. This finding is in line with prior research; namely that pharmacological interventions[15] or variations in lighting conditions[16] can significantly impact the geometry of the anterior segment. The observed differences in lens thickness due to changes in accommodation or mydriasis are likely due to physiological changes, such as ciliary muscle relaxation and altered anterior chamber dynamics, rather than measurement error.[17,18] Despite high measurement precision, the natural variability in response to tropicamide and inherent imaging process variabilities may also contribute to these differences. The dispersion of differences in ID and LEP around the mean, as depicted in the Bland–Altman plots (Figure 4), indicates variability between the non-dilated and dilated states. It should be noted that the measurements obtained with or without pharmacological dilation are not directly interchangeable due to the observed variability and offset between measurements. However, the strong linear correlation between these conditions (Figure 5 and Table 1) allows for reliable corrections of these differences. This correlation may be clinically relevant, as it allows a more precise estimation of the actual LEP using data obtained in non-dilated conditions (Figure 5) compared with current standards.

Both Martinez-Enriquez et al.[5] and Yoo et al.[6] highlighted the importance of 3D imaging techniques, such as AS-OCT, for improving IOL power calculations. Yoo et al.[6] emphasised the use of the LEP as a new parameter for predicting the postoperative IOL position, underscoring

TABLE 1 Comparison of geometric parameters with a non-dilated and dilated pupil; $N = 91$ eyes.

	Non-dilated	Dilated	*p*-Value	*r*
LEP (mm)	4.7 ± 0.3	4.5 ± 0.3	<0.001	0.64*
ID (mm)	11.2 ± 0.5	10.8 ± 0.5	<0.001	0.78*
LT (mm)	4.6 ± 0.4	4.5 ± 0.4	<0.001	0.99*
ALT (mm)	1.8 ± 0.3	1.7 ± 0.3	<0.001	0.90*
PLT (mm)	2.7 ± 0.2	2.8 ± 0.2	<0.001	0.81*

Abbreviations: ALT, anterior lens thickness; ID, intersection diameter; LEP, lens equatorial plane; LT, lens thickness; PLT, posterior lens thickness; *r*, Pearson coefficient.

*p-Value < 0.001 (mixed model ANOVA).

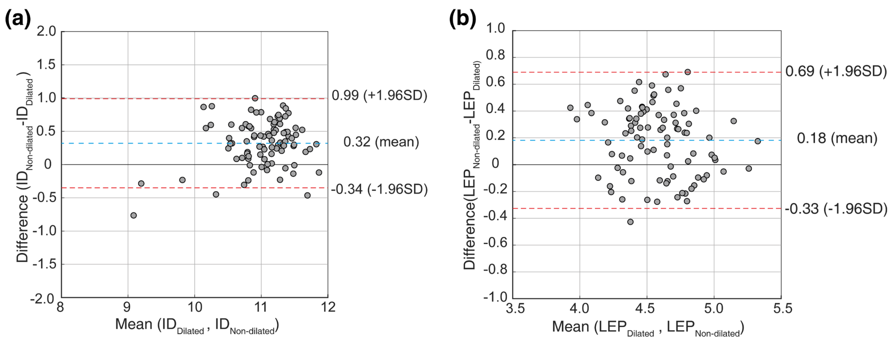

FIGURE 4 Bland–Altman plots for (a) the Intersection Diameter (ID) and (b) the Lens Equatorial Plane (LEP) parameters between dilated and non-dilated pupil conditions for 91 eyes.

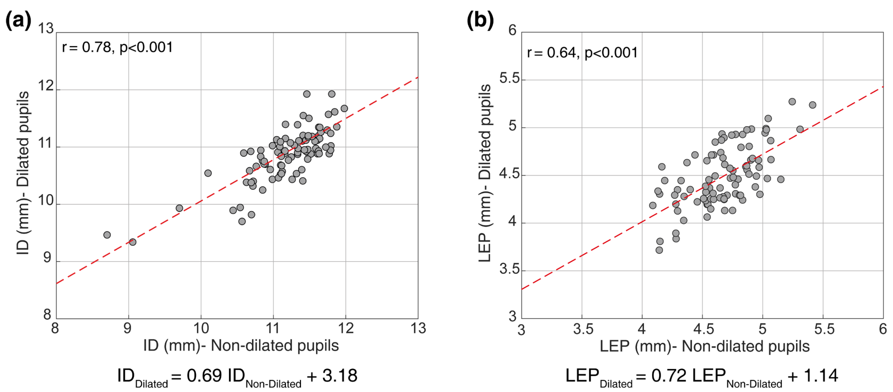

FIGURE 5 Correlation between the (a) Intersection Diameter (ID) and (b) Lens Equatorial Plane (LEP), with a dilated and non-dilated pupil. Values are measured in millimetres for 91 eyes.

the importance of direct measurements of the equatorial plane for enhancing IOL power estimation. Alternatively, Martinez-Enriquez et al. introduced the concept of '*eigenlenses*' to represent the full crystalline lens shape.[19] These authors showed that using *eigenlenses* to estimate the full shape of the crystalline lens in vivo from OCT images can lead to accurate predictions of lens position, thereby potentially refining IOL power calculations.[20] The work of Martinez-Enriquez et al.[19] was based on models created using human donor lenses and customised OCT systems. In contrast, the present study did not rely on predefined models, but rather used clinically available AS-OCT images. This practical approach facilitates real-world applicability and reproducibility. By using commercially available AS-OCT images, this provides a more accessible method for clinicians. It is worth considering that the ANTERION OCT Metrics App offers the possibility to capture images across five meridians. As part of this preliminary work, we initially considered all meridians on a couple of subjects for whom complete 3D data were available. However, the LEP results were consistent across meridians (standard deviation 0.070 and 0.084 mm), demonstrating that the LEP value remained constant regardless of the meridian analysed. Given this consistency, and the substantial manual effort required to export images from all meridians, it was decided to focus on the analysis of the horizontal meridian only, thus avoiding the additional time-consuming work of exporting and processing multiple meridians, which would facilitate clinical workflow. The studies of Martinez-Enriquez et al.[5,10,19,20] and Yoo et al.[3,6,9] as well as the current work, collectively suggest that a more comprehensive approach to lens geometry, including LEP measurements, can potentially enhance the precision of IOL power calculations.

The clinical significance of this study lies in its potential to refine IOL power calculation formulas. Traditional formulas neglect the direct measurement of the equatorial plane and frequently rely on preoperative biometric variables without taking into account the potential dynamic changes in ocular parameters with varying pupil sizes.[21] The current findings indicate statistically significant differences in both LEP and ALT between dilated and undilated conditions. This suggests that there would also be statistically significant differences in anterior chamber depth, a common parameter for IOL power calculation, between these physiological states. These differences underline the necessity of considering the eye's physiological state during the measurements, as it affects crucial parameters used for surgical planning. By incorporating a method that enables the operator to approximate the final position of the IOL in the lens bag accurately, as well as understand the relationship between LEP measurements with different sized pupils, surgeons will be better equipped to estimate the effective power of the lens in cataract surgery. Simultaneously, utilisation of more realistic effective lens position values in the pre-operative calculations, recognised as the most influential factor in determining post-surgical refractive errors, could significantly enhance precision.[22,23] In future research, it will be crucial to investigate whether the LEP is correlated with the final position of the IOL and, if so, how these differences in LEP measurements under varying physiological conditions translate to refractive outcomes.

In conclusion, this research offers a systematic approach for computing, among other parameters, the LEP, effectively filling a crucial void in the predictive elements of the actual lens position. Currently, the parameters outlined are not available in the built-in software of most OCT systems. Moreover, the findings underscore the importance of accounting for the physiological state of the eye in preoperative measurements, in order to optimise the variables that impact biometric calculations.

AUTHOR CONTRIBUTIONS

Ana R. Arizcuren: Formal analysis (lead); investigation (lead); methodology (equal); validation (equal); visualization (lead); writing – original draft (lead); writing – review and editing (equal). **Marta Jiménez-García:** Conceptualization (equal); data curation (equal); investigation (equal); resources (lead); supervision (equal); writing – review and editing (equal). **Francisco J. Castro-Alonso:** Conceptualization (equal); investigation (equal); resources (lead); supervision (equal); writing – review and editing (equal). **Alejandra Consejo:** Conceptualization (equal); investigation (equal); project administration (equal); resources (equal); supervision (equal); validation (equal); writing – original draft (lead); writing – review and editing (equal).

FUNDING INFORMATION

No specific financial support was received for the work being reported.

CONFLICT OF INTEREST STATEMENT

Authors report no conflict of interest.

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How to cite this article: Arizcuren AR, Jiménez-García M, Castro-Alonso FJ, Consejo A. Description of a new method to calculate the equator of the crystalline lens using AS-OCT images: Accuracy in non-dilated measurements. *Ophthalmic Physiol Opt*. 2024;00:1–7. https://doi.org/10.1111/opo.13353