Journal of
Clinical & Translational Ophthalmology

MDPI

Article

Refractive Astigmatism Consistency Pre- and Post-Cycloplegia in Pediatric Population

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Abstract: Background: Cycloplegic refraction is crucial in pediatric eye assessments. While spherical refraction changes due to cycloplegia are well-documented, astigmatic alterations remain unclear. This study assessed the agreement between spherical and astigmatic refraction pre- and post-cycloplegia. Methods: We enrolled 96 patients (mean age: 12.5 ± 2.4 years), including 35 myopes, 30 emmetropes, and 31 hyperopes. Pre- and post-cycloplegia autorefraction and keratometry (Myopia Master) were conducted using 1% cyclopentolate. Ocular residual astigmatism (ORA) was calculated as the difference between refractive and keratometric astigmatism. Astigmatism was analyzed using Fourier analysis (J0 and J45). Results: Cycloplegia resulted in a more positive spherical equivalent (SE) (+0.80 D), with myopes showing the smallest (+0.38 D) and hyperopes showing the highest variation (+1.47 D) in SE. With-the-rule (WTR) astigmatism predominated in the refractive and keratometric measurements, while ORA was against-the-rule (ATR). Cycloplegia shifted the refractive J0 (+0.06 D) towards more WTR and decreased ORA J0 (+0.05 D). No effect was observed in the J45 component. About 25% of patients exhibited astigmatism changes above 0.25 D, with refractive J0 variation being positively correlated with accommodation relaxation (0.044 D per D of relaxation). Conclusion: Cycloplegia induces clinically significant changes in the spherical component, but minimal variations in astigmatic components, predominantly in hyperopic eyes, likely reflecting alterations in crystalline lens anatomy.

Keywords: astigmatism; autorefraction; cycloplegia; accommodation

Citation: Peñaranda, A.; Torrado, O.; Márquez, A.; Baptista, A.M.; Serra, P.M. Refractive Astigmatism Consistency Pre- and Post-Cycloplegia in Pediatric Population. *J. Clin. Transl. Ophthalmol.* **2024**, *2*, 181–194. https://doi.org/10.3390/jcto2040015

Received: 22 April 2024
Revised: 18 November 2024
Accepted: 10 December 2024
Published: 18 December 2024

1. Introduction

Accurate ocular refractive error measurement requires meticulous accommodation control, especially in pediatric cases due to their heightened accommodative capacity and susceptibility to proximal accommodation [1]. Hyperopic eyes can use accommodation to reduce blur [2], and astigmatic eyes may show fluctuations altering the focal planes [3]. Inadequate accommodative control can lead to erroneous spherical refractions, misdiagnosing hyperopia and overestimating myopia [2,4]. Accommodative control through pharmacological agents (e.g., cyclopentolate hydrochloride) [5] improves the accuracy of refractive error measurement [6].

Large-scale studies demonstrate the efficacy of cycloplegia, particularly cyclopentolate, in reducing accommodative influence during autorefraction, with average spherical equivalent (SE) differences of around 0.80 D, more pronounced in younger individuals and those with higher hyperopia [2,4]. Less investigated is the variation in refractive astigmatism with cycloplegia, influenced by both corneal and ocular residual astigmatism (ORA), including contributions from the crystalline lens [7–9]. Ocular residual astigmatism at the fovea includes axial astigmatism from the posterior cornea [10] and crystalline lens toricity [11], along with oblique astigmatism due to misalignments of the optical media [8]. Accommodation changes, whether stimulation [12,13] or relaxation [14–16], can affect refractive

astigmatism, primarily impacting the horizontal and vertical components (J0), while the oblique component (J45) remains stable [8,13,17]. Studies on cycloplegia's impact on astigmatism have reported changes mainly in J0 [18–22], though some have found no significant change [23]. The clinical contributions of this effect range from −0.025 D to +0.05 D [18,21], with no consensus on the direction of change, as some have reported increased with-the-rule (WTR) astigmatism [18,19] and others against-the-rule (ATR) astigmatism [20,21]. Discrepancies may arise from sample heterogeneity, age distribution, and instrumental differences [18–21,24]. The association between refractive error and cycloplegic effect seen in SE variation [2] may extend to astigmatism [19]. Given the importance of accurate refractive error correction in children and best practices advocating cycloplegic refraction in pediatrics [25], this study investigated variations in spherical refraction and in refractive, keratometric, and ocular residual astigmatism across three refractive groups, as well as the association between accommodative response to cycloplegia and astigmatism variation.

2. Materials and Methods

2.1. Participants

Ninety-six pediatric patients under 16 years old undergoing routine ophthalmological evaluation at the Ophthalmology Clinic Vista Sánchez Trancón, Badajoz, Spain, were enrolled in this prospective cross-sectional study. The sample consisted of 35 myopes (SE < -0.75 D), 30 emmetropes (SE ≥ -0.75 D and SE $< +1.00$ D), and 31 hyperopes (SE $\geq +1.00$ D) [26]. The inclusion criteria encompassed refractive astigmatism below 2.50 D under cycloplegia, distance-corrected visual acuity (DCVA) equal to or better than 6/6, and the absence of ocular pathology and strabismus. The Myopia Master measurement protocol, utilizing the "Myopia Mode", performed autorefraction, keratometry, and AL measurement sequentially. Only patients with a quality index of ≥ 7 for autorefraction and keratometry and a signal-to-noise ratio of ≥ 6.0 for AL were included. The study adhered to the tenets of the Helsinki Declaration and received approval from the local ethics committee (Comité Ético para Investigacion Clinica de Badajoz, Spain). Patient information was provided by the accompanying caregiver and informed consent was obtained from all participants.

2.2. Study Protocol

Myopia Master measurements were integral to the ophthalmological examination, which included visual acuity assessment, autorefraction, keratometry, AL measurement, subjective refraction pre- and post-cycloplegia, a cover test, slit-lamp examination, and ophthalmoscopy. Cycloplegia was induced using cyclopentolate hydrochloride (Colicusí Cicloplégico 10 mg/mL, Cornellà de Llobregat, Spain), administered with a first drop followed by a second one ten minutes later. Cycloplegic measurements with the Myopia Master were taken 30 min after the initial drop. Two measurements were performed pre- and post-cycloplegia. Patients were instructed to keep both eyes open, blink naturally, and fixate on the center of a hot air balloon used as a fixation target. The administration of cycloplegic drops and measurements were consistently performed by the same senior optometrist (AP).

2.3. Instrument

The Myopia Master (version 7.2 R3) utilizes a fixation target mimicking optical infinity along with a fogging system to control accommodation during autorefraction. An infrared light source (λ = 850 nm) projected light onto the retina, which was captured by a charge-coupled device camera. Deviations from the shutter location were recorded, and an integrated micro-computer calculated the ametropia. The reported autorefraction represents the average of three measurements. The central corneal curvature was determined by the reflection of test spots (λ = 940 nm) and a central ring projected onto the central 15 degrees of the cornea. Keratometric values were measured within a 3.0 to 4.0 mm area, depending on the corneal curvature [27].

2.4. Statistical Analysis

Refractive and keratometric parameters were analyzed both pre- and post-cycloplegia, as well as for measurement agreement. In this study, only data on the right eyes of the patients were included. The refractive parameters included the SE in diopters (D) and refractive astigmatic components (J0 Rx and J45 Rx in D). The keratometric parameters comprised Km (in D) and keratometric astigmatic components (J0 K and J45 K in D). Ocular residual astigmatism was determined as the difference between the refractive and keratometric astigmatism [28]. The ORA was decomposed into the astigmatic components (J0 ORA and J45 ORA in D). The spherical equivalent was calculated as the sum of the sphere and half of the refractive cylinder in negative power (SE = sphere + cylinder/2). The J0 component represents the Jackson-cross cylinder power at 180 and 90 degrees, while J45 denotes the Jackson-cross cylinder power at 45 and 135 degrees. The J0 and J45 components, whether refractive, keratometric, or ocular residual, represent comparisons of projected astigmatism and were computed using the formulas J0 = $-0.5 \times$ cylinder $\times \cos(2 \times$ cylinder axis) and J45 = $-0.5 \times$ cylinder $\times \sin(2 \times$ cylinder axis), with the cylinder axis denoting the orientation of the most powerful meridian [29].

The conversion from cartesian notation (J0 and J45) to the polar notation was conducted using the formula $C = -2\sqrt{(J0^2 + J45^2)}$ for the astigmatism magnitude and axis = $0.5 \times \tan^{-1}(J45/J0)$ [29]. These were used to calculate the mean astigmatism magnitude and the summated vector mean (SVM) for refractive, keratometric, and ocular residual astigmatism [30]. Eyes were categorized based on the astigmatism axis as WTR if the negative cylinder axis fell within 0/180 degrees ± 30 degrees, oblique if the negative cylinder axis fell within 45/135 degrees ± 30 degrees, and ATR astigmatism if the astigmatism fell within 90 degrees ± 30 degrees [31].

Data are presented as mean, standard deviation (±SD), and 95% confidence interval (CI) for the mean and range. The Kolmogorov–Smirnov test was used to assess data distribution. The influence of cycloplegia on the SE, J0, and J45 components (refractive, keratometric, and ocular residual) was analyzed for the entire group using the paired Student *t*-test for normally distributed data and Wilcoxon test for non-normally distributed data. Differences in the effect of cycloplegia among the three groups were assessed using one-factor analysis of variance (ANOVA) or the Kruskal–Wallis test, depending on the data normality. Post hoc analysis between paired groups was conducted with the unpaired Student *t*-test or Mann–Whitney test.

Agreement between pre- and post-cycloplegia measurements or between refractive and keratometric astigmatism was calculated as the difference between the average post-cycloplegia and average pre-cycloplegia measurements. The 95% limits of agreement (LoAs) were estimated as $1.96 \times$ SD of the average of the differences between these pairs of measurements. The 95% CIs of the LoAs, representing the true dispersion of the LoAs, were calculated using exact methods [32].

The sample size was calculated using the J0/J45 refractive astigmatism components to detect a difference of 0.125 D between two refractive groups, assuming a J0/J45 group standard deviation of 0.12 D. A sample size of 31 subjects per refractive group was required to reject the null hypothesis with a power of 0.95 and assuming a type I error probability of (0.05/3 = 0.017). Power sample calculation was performed using PS Power and Sample Size Calculations [33], and statistical analysis was conducted using IBM SPSS v23.

3. Results

The mean age of the 96 children (50% females) was 12.5 ± 2.4 years old (range: from 7 to 16). This comprised 35 myopes, SE = −2.48 ± 1.24 D (range: from −5.64 D to −0.79 D), 30 emmetropes, SE = +0.29 ± 0.48 D (range: from −0.66 D to +0.95 D), and 31 hyperopes, SE = +2.48 ± 1.56 D (range: from +1.00 D to +7.25 D). Figures 1–3 and S1 and Table S1 (in Supplementary Materials) present the data on the autorefraction and keratometic parameters measured pre- and post-cycloplegia.

3.1. Refractive Error Variation with Cycloplegia

For the entire group, the SE pre-cycloplegia was −0.80 ± 2.00 D and post-cycloplegia was −0.01 ± 2.38 D, representing a significant hyperopic shift (ΔSE = +0.79 ± 0.82 D, 95% CI: +0.62 to +0.96 D, $p < 0.0005$) with cycloplegia (Table S2 in Supplementary Materials). The pre-cycloplegia J0 and J45 were +0.20 ± 0.36 D and −0.08 ± 0.20 D, respectively, showing a tendency for WTR astigmatism (mean Rx astigmatism: 0.72 ± 0.57 D; SVM: −0.44 × 169 degrees, Figure S1 (in Supplementary Materials)). The post-cycloplegia (mean Rx astigmatism: 0.77 ± 0.54 D; SVM: −0.54 × 172 degrees, Figure S1) J0 refractive astigmatism differed significantly from the pre-cycloplegia measurement (ΔJ0 Rx = +0.06 ± 0.12 D, 95% CI: +0.03 to +0.08 D, $p < 0.0005$), Figure 1a. The LoA for J0 Rx ranged between −0.18 and +0.29 D, Figure 1c. The mean pre- and post-cycloplegia refractive J45 were similar, +0.01 ± 0.09 D (95% CI: −0.01 to +0.02 D, $p = 0.324$), with the LoA ranging from −0.15 to +0.17 D, Figure 1b.

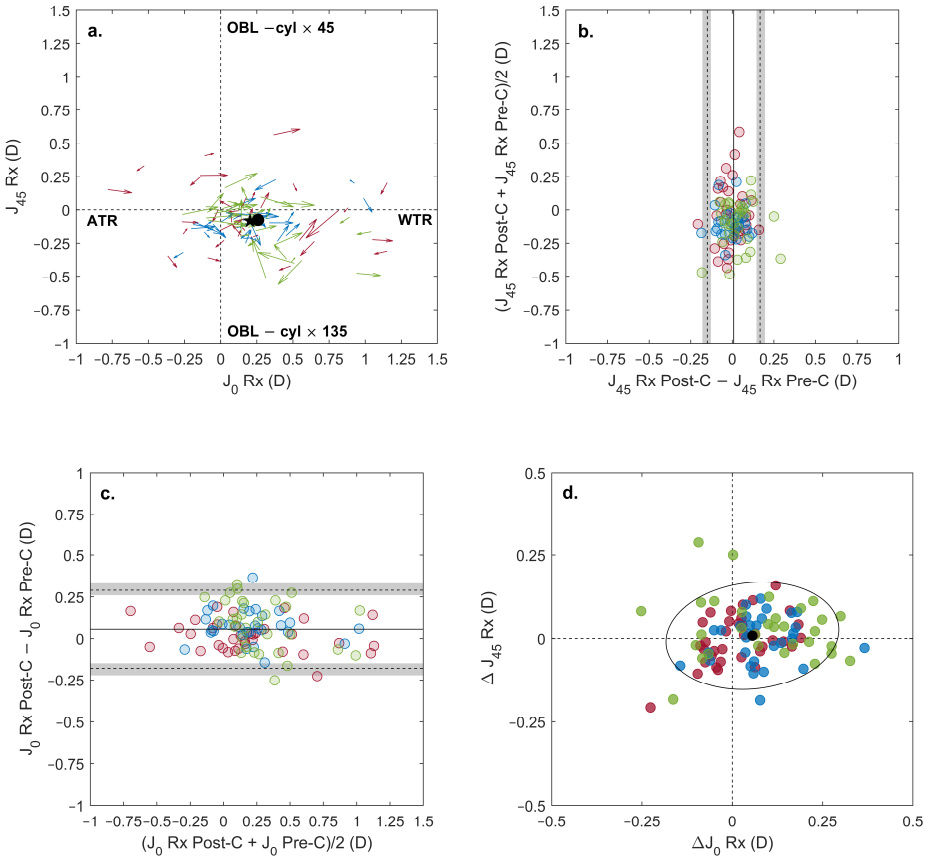

Figure 1. Difference analysis for the refractive astigmatism components J0 and J45 for the three refractive groups (red: myopes, blue: emmetropes, and green: hyperopes). (**a**). Cartesian plot shows the J0/J45 variation, the beginning of the arrow indicates the J0/J45 pre-cycloplegia, and the tip of the arrow the J0/J45 post-cycloplegia. Bland–Altman (B-A) plots are presented laterally (**b**). and inferiorly (**c**). to the Cartesian plot to show the differences of each component. The middle point of each vector read on the *x*-axis and *y*-axis corresponds to a data point on the *x*-axis of the J0 B–A plot and *y*-axis of the J45 B–A plot. Continuous lines in the graph indicate the mean difference between measurements and repeated measurements, dashed lines the 95% limits of the agreement (LoAs), and the grey areas define the 95% CI of the LoA. Black star (★): indicates the mean J0/J45 pre-cycloplegia and black circle (•): indicates the mean J0/J45 post-cycloplegia (note that ★ and • are partially overlapped). (**d**). Cartesian plot shows the variation in J0/J45, the black circle (•) indicates the mean J0/J45, and the ellipse represents the 95% confidence interval of the pre- and post-cycloplegia differences.

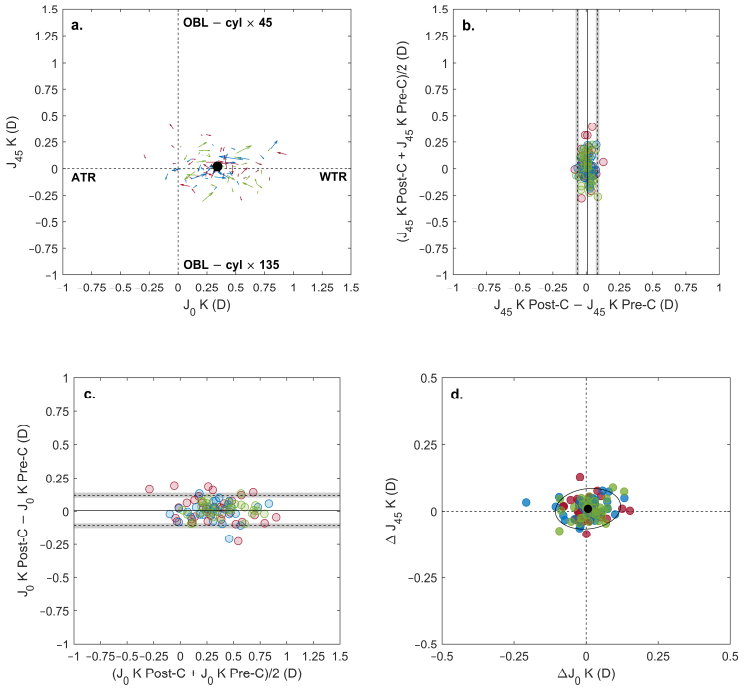

Figure 2. Difference analysis for the keratometric astigmatism components J0 and J45 for the three refractive groups (red: myopes, blue: emmetropes, and green: hyperopes). (**a**). Cartesian plot shows the J0/J45 variation, the beginning of the arrow indicates the J0/J45 pre-cycloplegia, and the tip of the arrow the J0/J45 post-cycloplegia. Bland–Altman (B–A) plots are presented laterally (**b**). and inferiorly (**c**). to the Cartesian plot to show the differences of each component. (**d**). Cartesian plot shows the variation in J0/J45. The details of the B–A and Cartesian plots are the same as in Figure 1.

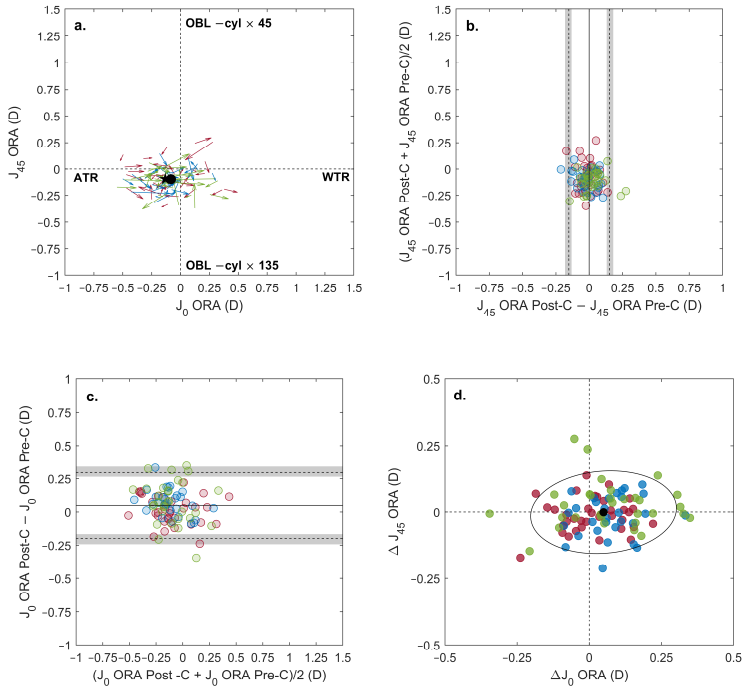

Figure 3. Difference analysis for the ocular residual astigmatism components J0 and J45 for the three refractive groups (red: myopes, blue: emmetropes, and green: hyperopes). (**a**). Cartesian plot shows the J0/J45 variation, the beginning of the arrow indicates the J0/J45 pre-cycloplegia, and the tip of the arrow the J0/J45 post-cycloplegia. Bland–Altman (B–A) plots are presented laterally (**b**). and inferiorly (**c**). to the Cartesian plot to show the differences of each component. (**d**). Cartesian plot shows the variation in J0/J45. The details of the B–A and Cartesian plots are the same as in Figure 1.

Pre-cycloplegia keratometric astigmatism predominantly exhibited a WTR orientation (mean K astigmatism: 0.76 ± 0.40 D; SVM: −0.67 × 1 degrees, Figure S1), with J0 K and J45 K values of +0.34 ± 0.24 D and +0.01 ± 0.13 D, respectively (Figure 2a). There was no significant difference in the keratometric astigmatism (mean K astigmatism: 0.77 ± 0.40 D; SVM:−0.68 × 2 degrees, Figure S1) with cycloplegia (ΔJ0 K = +0.01 ± 0.06 D, 95% CI: −0.01 to +0.02 D, $p = 0.279$ and ΔJ45 K = +0.01 ± 0.04 D, 95% CI: 0.00 to +0.02 D, $p = 0.107$). The LoAs for keratometric J0 ranged from −0.11 to +0.12 D and for J45 ranged from −0.07 to +0.08 D, respectively, (Figure 2b–d).

Pre-cycloplegia, the estimation of ORA retrieved a mean J0 ORA of −0.13 ± 0.21 D and J45 ORA of −0.10 ± 0.12 D, indicating a predominant ATR component (mean ORA: 0.53 ± 0.23 D; SVM: −0.33 × 108 degrees, Figure S1), Figure 3a. Post-cycloplegia (mean ORA: 0.44 ± 0.23 D; SVM: −0.25 × 112 degrees, Figure S1), the J0 and J45 components were −0.08 ± 0.18 D and −0.10 ± 0.11 D, representing a significant difference for the J0 ORA component (ΔJ0 ORA = +0.05 ± 0.13 D, 95% CI: +0.02 to +0.08 D, $p < 0.0005$), but not for the J45 ORA (ΔJ45 ORA = 0.00 ± 0.08 D, 95% CI: −0.02 to +0.01 D, $p = 0.904$). The LoAs for the difference between pre- and post-cycloplegia ranged from −0.17 to +0.30 D for J0 ORA and from −0.15 to +0.15 D for J45 ORA, Figure 3b–d.

3.2. Influence of Refractive Error

Comparison among the groups revealed significant differences between the three refractive groups for both pre- and post-cycloplegia SE values ($p < 0.0005$, for both). However, there were no significant differences among the groups for the J0 and J45 keratometric, refractive, and ocular residual astigmatism components pre- and post-cycloplegia ($p >> 0.05$ for all). Notably, the SE changes induced by cycloplegia varied among the refractive groups ($p < 0.0005$), Table S2. Myopes exhibited the smallest change (ΔSE myopes: +0.38 ± 0.25 D, 95% CI: +0.30 to +0.47 D), significantly different from the hyperopic group (ΔSE hyperopes: +1.47 ± 1.07 D, 95% CI: +1.07 to +1.86 D) ($p < 0.0005$). Emmetropes showed a higher refractive variation compared to myopes (ΔSE emmetropes: +0.56 ± 0.43 D, 95% CI: +0.40 to +0.72 D), but this difference was not statistically significant ($p = 0.092$), yet significantly lower than that of hyperopes ($p < 0.0005$). Regarding differences in the astigmatic components among groups, refractive J0 showed significant differences ($p = 0.029$), while J0 ORA did not reach statistical significance ($p = 0.052$), Figure 4 and Table S2. All the remaining astigmatic components did not differ among the groups ($p >> 0.050$). The horizontality of the major ellipse axis in Figure 4c–e illustrates the greater variation in the J0 component compared to the J45 component. Notably, major differences were observed between the myopic group compared to the emmetropic and hyperopic groups. Post hoc analysis revealed a mean refractive J0 difference of +0.01 ± 0.09 D (95% CI: −0.02 to +0.05 D) for the myopic group, while the mean changes in the emmetropic and hyperopic groups were +0.07 ± 0.08 D (95% CI: +0.04 to +0.11 D, $p = 0.033$ after Bonferroni correction) and +0.08 ± 0.15 D (95% CI: +0.03 to +0.14 D, $p = 0.141$ after Bonferroni correction), respectively.

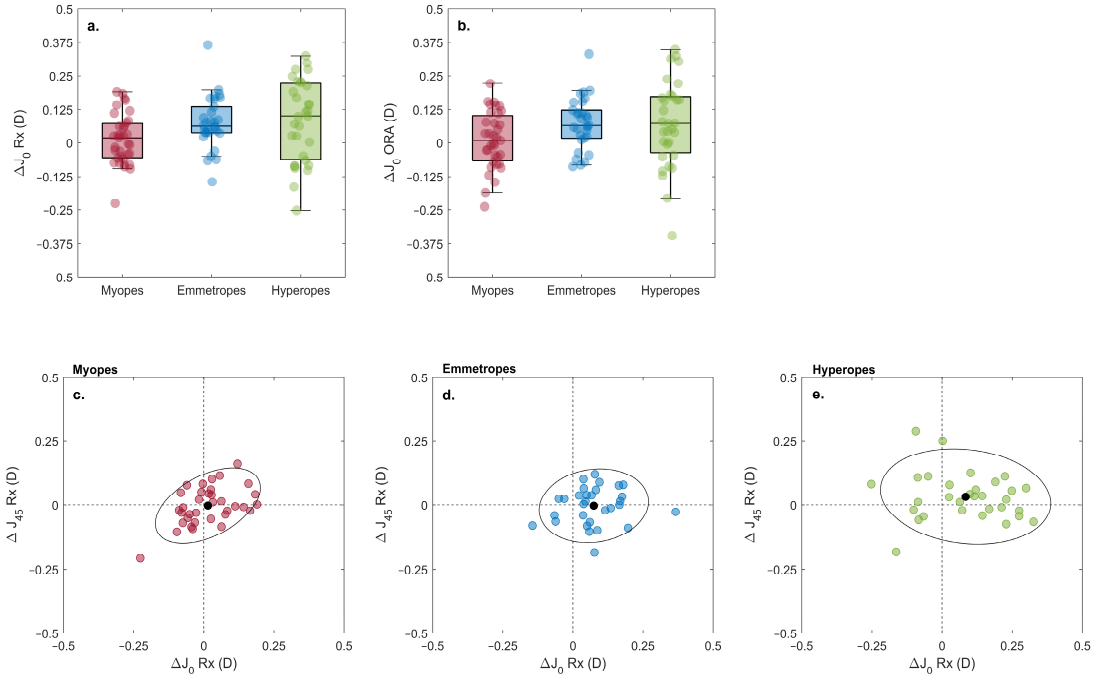

Figure 4. Box plots with jitter data of the difference (post-cycloplegia minus pre-cycloplegia) in the astigmatic components J0 Rx (**a**) and J0 ORA (**b**). The central line represents the mean, the outer bounds of the box represent the 50% central distribution, and whiskers represent the 95% distribution amplitude. Scatter plots show the variation in J0 Rx for the three refractive groups, myopes (**c**), emmetropes (**d**), and hyperopes (**e**). The black circle (•) indicates the mean J0/J45 for each group and the ellipse represents the 95% confidence interval of the pre- and post-cycloplegia differences.

Figure 5 illustrates the correlation between changes in the SE (ΔSE) and refractive astigmatism components (ΔJ0 Rx and ΔJ45 Rx) with cycloplegia. A positive correlation was observed between ΔSE and ΔJ0 Rx (Spearman's rho = 0.219, p = 0.032), with ΔSE explaining only 4.8% of the variation in J0. The linear regression model predicted an average variation of 0.044 D per D of accommodation relaxation (95% CI: +0.016 to +0.073 D/Dacc relaxation) for the J0 Rx component and 0.014 D per D of accommodation (95% CI: −0.005 to +0.035 D/Dacc relaxation) for the J45 Rx component.

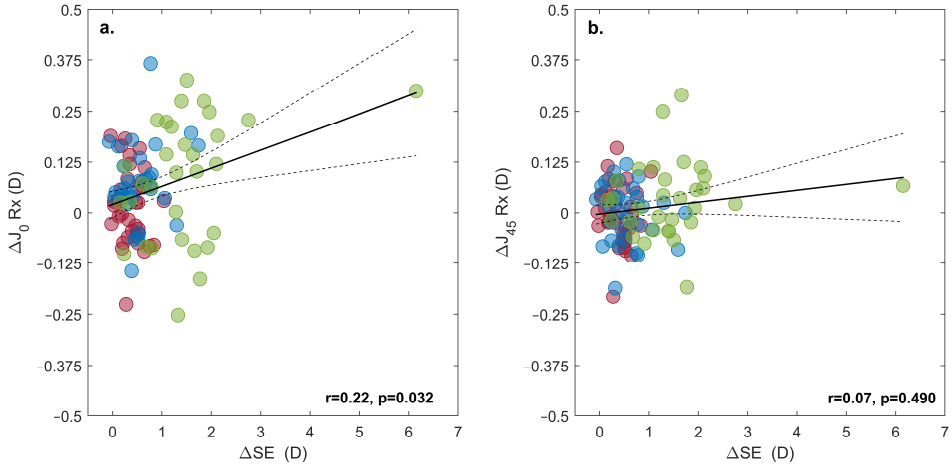

Figure 5. Linear regression representing the relationship between variation in spherical equivalent and variation in J0 Rx (**a**) and J45 Rx (**b**). Continuous line represents the linear regression model, the dashed line the confidence intervals of the model and the colors represent the three refractive groups (red: myopes, blue: emmetropes, and green: hyperopes).

Plotting the cylinder magnitude against the cylinder rotation induced by cycloplegia demonstrates that the extent of rotation depended on the magnitude and type of cylinder. Larger changes in refractive astigmatism orientation occurred primarily in cases with low astigmatic values, up to −0.50 D, while higher refractive astigmatism tended to show no rotation (Figure 6). Notably, low ATR astigmatism associated with hyperopia exhibited higher rotations.

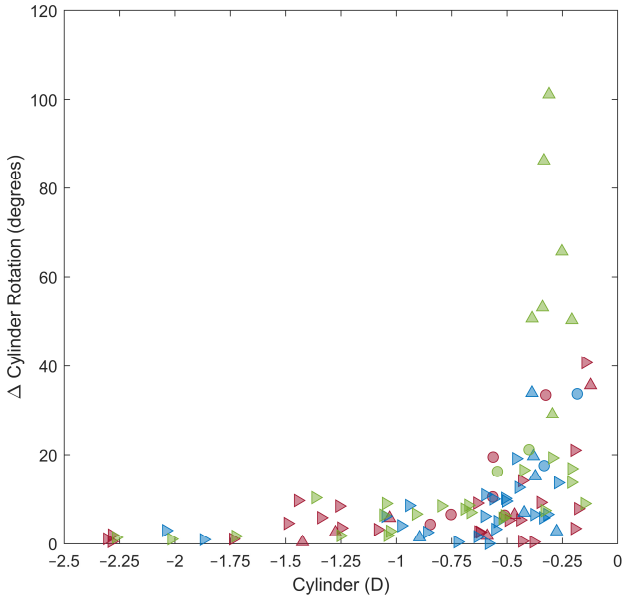

Figure 6. Scatter plot of refractive astigmatism magnitude against astigmatism rotation induced by cycloplegia. Red, blue and green symbols represent myopes, emmetropes, and hyperopes. The symbols shapes represent pre-cycloplegia ▷, with-the-rule astigmatism, ○ oblique astigmatism, and △ against-the-rule astigmatism.

Overall, post-cycloplegia, there was a shift towards more eyes being categorized as having WTR and oblique astigmatism, along with a decrease in eyes classified as having ATR astigmatism (Table 1).

Table 1. Number of eyes changing orientation post-cycloplegia.

	ALL (n = 96)			**Myopes (n = 35)**			**Emmetropes (n = 30)**			**Hyperopes (n = 31)**		
	WTR	**OBL**	**ATR**	**WTR**	**OBL**	**ATR**	**WTR**	**OBL**	**ATR**	**WTR**	**OBL**	**ATR**
Pre-C	67	10	19	23	6	6	22	2	6	22	2	7
Post-C	74	11	11	23	5	7	22	5	3	29	1	1

3.3. Relationship Between Refractive and Keratometric Astigmatism

Figure 7 depicts the relationship between the keratometric and refractive astigmatism components, providing a representation of Javal's rule. The linear regression model demonstrated a strong correlation between corneal and refractive astigmatism for both J0 (pre-cycloplegia: R^2 = 0.71 and post-cycloplegia: R^2 = 0.73) and J45 (pre-cycloplegia: R^2 = 0.57 and post-cycloplegia: R^2 = 0.66).

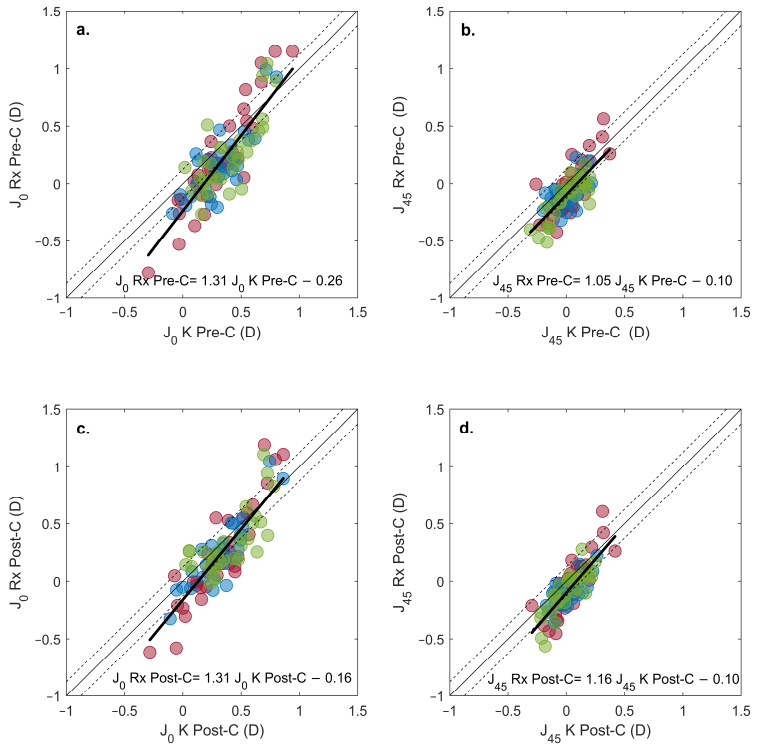

Figure 7. Scatter plots of keratometric and refractive astigmatism components, pre-cycloplegia for J0 (**a**) and J45 (**b**) and post-cycloplegia for J0 (**c**) and J45 (**d**). Continuous line represents the unitary line, dashed lines unitary line ±0.125 D and the colors represent the three refractive groups (red: myopes, blue: emmetropes, and green: hyperopes).

Cycloplegia tends to align corneal and refractive astigmatism, likely due to a decrease in ORA, which approaches zero when corneal astigmatism is zero. The agreement between keratometric and refractive J0 showed a mean pre-cycloplegia difference of +0.13 ± 0.21 D (95% CI: +0.09 to +0.17 D), with LoAs ranging from −0.27 to +0.54 D. Post-cycloplegia, the mean difference was reduced to +0.08 ± 0.21 D (95% CI: +0.05 to +0.12 D), with LoAs ranging from −0.27 to +0.44 D. The proportion of eyes with differences below 0.125 D increased from 32% (n = 31) pre-cycloplegia to 42% (n = 40) post-cycloplegia. For J45, differences were smaller, consistent with J45's stability with cycloplegia. The mean pre-cycloplegia difference was +0.10 ± 0.12 D (95% CI: +0.07 to +0.12 D), with LoAs ranging from −0.14 to +0.34 D, while post-cycloplegia, the mean difference was +0.08 ± 0.11 D (95% CI: +0.07 to +0.12 D), with LoAs ranging from −0.12 to +0.32 D. The proportion of eyes with differences below 0.125 D remained relatively stable, from 54% (n = 52) pre-cycloplegia to 58% (n = 56) post-cycloplegia.

4. Discussion

The study examined cycloplegia's impact on ocular refraction in pediatric subjects, noting a hyperopic shift in spherical refraction alongside minor changes in refractive astigmatism. Astigmatism analysis revealed a shift in horizontal–vertical refractive and ocular residual astigmatism (J0) towards more positive values, while oblique astigmatism (J45) remained unaffected. Approximately one-fourth of patients exhibited astigmatic differences exceeding 0.25 D, with correlations observed between these differences and the magnitude of spherical change, particularly in emmetropes and hyperopes. Pre-cycloplegia, low ATR astigmatisms were more prone to exhibit axis rotations compared to high astigmatisms.

Cycloplegia induced a hyperopic shift in the SE, with a mean increase of +0.79 D. Large-scale studies by Fotedar et al. [2] and Hu et al. [4] utilizing cyclopentolate reported similar findings, with mean differences of +0.84 D and +0.78 D, respectively, among subjects around 12 years old. This hyperopic shift was more pronounced in hyperopic individuals (+1.47 D) compared to myopic individuals (+0.38 D), resulting in an overestimation of myopia and

an underestimation of hyperopia in non-cycloplegic autorefraction [34]. The differential refractive response is likely attributable to myopes exhibiting less accommodation for near objects, while hyperopes, particularly young ones with large accommodative amplitudes, can mitigate hyperopic focus during autorefraction [1,24].

Pre-cycloplegia analysis of refractive astigmatism revealed a prevalent WTR astigmatism (-0.44×169), typical in this age group [10,31]. This WTR astigmatism exhibited a strong correlation with corneal astigmatism magnitude (-0.67×1) and indicated the presence of ATR ocular residual astigmatism (-0.33×108 D). This ocular residual astigmatism aligns with findings from Grosvenor et al., who observed a similar ORA in a cohort of myopic children (-0.40×90) [9]. Moreover, ocular residual astigmatism appeared to be independent of keratometric astigmatism (Pearson R: J0 = 0.174 and J45 = 0.183, $p > 0.05$), suggesting no proportional compensatory effect of corneal astigmatism through the residual component [7].

The cycloplegia-induced changes in refractive astigmatism were modest (~0.11 D), primarily influenced by a shift in J0 (+0.06 D) towards more positive values, leading to a heightened refractive WTR astigmatism post-cycloplegia. Notably, there was no significant alteration in the J45 component following cycloplegia [18,19,22]. Although the mean difference fell below half of the minimal cylinder refractive step (0.25 D), the LoAs between pre- and post-cycloplegia ranged from −0.36 to +0.58 D, with approximately 25% of eyes displaying differences exceeding 0.25 D. Categorization into distinct refractive groups revealed that astigmatic changes were primarily observed in emmetropic and hyperopic patients (Figure 4a), particularly those exhibiting larger SE variations post-cycloplegia (Figure 5a). Significant differences in J0 were solely discerned between myopes and emmetropes, whereas hyperopes demonstrated mean variations comparable to emmetropes; however, the hyperopic subgroup showcased a greater accommodative and astigmatic variability, limiting statistical significance (Figure 4e). These findings underscore the necessity of discussing the controversy surrounding the consistency of astigmatic refraction with cycloplegia, taking into consideration the characteristics of the population under investigation (e.g., age and refractive error) and the instrument employed for refractive error measurement, such as retinoscopy and autorefraction (Figure 8). The variation in the refractive J0 component induced by cycloplegia was close to the repeatability of the J0 refractive measurement using the Myopia Master, +0.02 (95% CI −0.01; +0.05) [35]. This underscores the importance of instrument repeatability and suggests that eyes with minor accommodative variations produced by cycloplegia may go undetected.

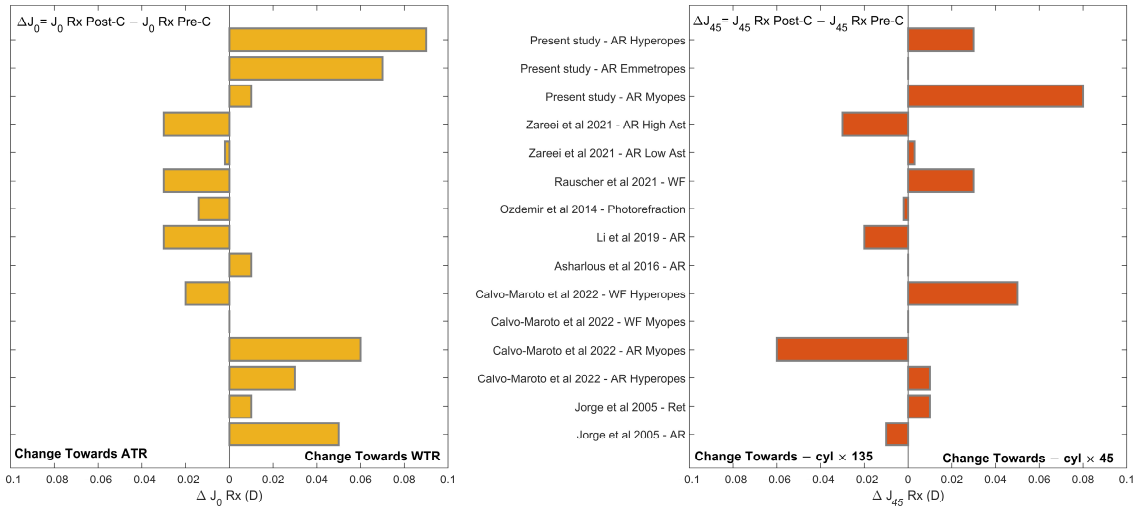

Figure 8. Compilation of studies showing variations in refractive astigmatic components J0 and J45 with cycloplegia [18–23,36]. AR: autorefraction, Ret: retinoscopy, WF: wavefront.

The extent of spherical error variation under cycloplegia, coupled with the pre-existing refractive error, appeared to be a key determinant of astigmatic variations. Studies by Asharlous et al. [19] and Calvo-Maroto [22] highlighted significant refractive J0 differences mainly in hyperopic patients, while myopic eyes exhibited smaller variations in both SE and refractive astigmatism [22,23]. Age and the diminishing effect of cycloplegia with increasing age may also contribute to reduced variations in refractive components. Methodological disparities, such as the type of instrument/methodology used for refraction, may influence the measurement of refractive astigmatic variations. If astigmatic variations are below the minimum step typically utilized in subjective refraction or retinoscopy, they might remain undetected [18,22,24]. Instruments employing different working principles, such as autorefractors and wavefront analyzers, may yield divergent results. Autorefractors assess the refractive error through a central area (approximately 3.0 mm), while aberrometers evaluate the wavefront shape across the entire pupil and derive the paraxial refractive error based on fitting Zernike coefficients to a central portion of the pupil, which might lack accuracy [37]. Additionally, photorefractors may exhibit astigmatism variations attributable to differences in retroillumination associated with variations in pupil size [38].

Corneal astigmatism remained unaffected by cycloplegia, with the LoA equivalent to the Myopia Master keratometry repeatability [27,34]. This indicates that refractive astigmatic changes are unlikely to have a corneal origin [8,39]. In foveal fixation, ocular residual astigmatism arises from refraction in the corneal posterior surface and crystalline lens, as well as light propagation through the optical media [8]. Changes in ocular residual astigmatism are likely due to variations in crystalline lens morphometry resulting from ciliary muscle relaxation [14–16]. The correlation obtained between the amount of accommodation relaxation and J0 variation resulted in a slope of +0.044 D/D of accommodation relation, explaining 4.8% of the J0 variation, while no relation was found between SE variation and J45 variation. Studies on accommodation's effect on astigmatism have reported variations in J0 from 0.021 to 0.06 D/D of accommodation towards ATR astigmatism [8,13,40]. Radhakrishnan and Charman observed similar variations in J0 magnitude (0.036 D/D of accommodation), but with changes towards WTR astigmatism [17].

Studies examining the crystalline lens dynamics during accommodation have shown zonular relaxation, leading to the inferior displacement and tilting of the lens around the horizontal axis [12]. Lara-Lacarcel et al., using ray tracing, suggested that vertical displacement of the crystalline lens (a structure with negative spherical aberration) relative to the cornea (a structure with positive aberration) generates coma, astigmatism, and tilt, resulting in a decreased J0 and constant J45 [13]. This could explain the increase in ATR astigmatism observed during accommodation. Conversely, it can be hypothesized that accommodation relaxation may increase zonular tension, leading to a thinning and centration of the crystalline lens with the cornea, thereby reducing the ATR astigmatism present during active reflex accommodation. However, this hypothesis requires imaging verification.

Our findings reveal specific trends regarding which eyes are more prone to exhibit changes in the astigmatic axis following cycloplegia. Figure 8 and Table 1 illustrate that hyperopic eyes with low ATR astigmatism tend to undergo axis rotation towards WTR astigmatism under the influence of cycloplegia, accompanied by a decrease in ocular residual ATR. This observation, coupled with the constancy of the ΔJ0/J45 refractive with the J0/J45 magnitude (Figure 1a), contradicts the results of Zareei et al. [20], who noted greater astigmatic changes in cases of higher astigmatism.

One limitation of our study is the lack of tracking regarding the consistency of the line of sight and keratometric axis during measurements [41]. Consequently, interpreting the results requires assuming that the line of sight and keratometry axis remained unchanged under cycloplegia, thereby maintaining a consistent amount of ocular residual astigmatism associated with off-axis fixation. Additionally, minor fluctuations in fixation, particularly in pediatric subjects, may introduce additional variability. To address this concern, we conducted two consecutive measurements before and after cycloplegia to minimize po-

tential variations, which were added to the three consecutive measurements made by the Myopia Master.

5. Conclusions

The variations recorded in astigmatic components with cycloplegia were, on average, below clinical significance. The range of differences among our pediatric subjects suggests that some individuals may exceed the clinical threshold of 0.25 D. Pre-cycloplegia, emmetropes and hyperopes with low amounts of ATR astigmatism or those exhibiting larger variations in the spherical component with cycloplegia were more susceptible to astigmatic changes. Post-cycloplegia, there was a notable increase in WTR astigmatism, resulting from a reduction in ocular residual ATR astigmatism, which may reflect anatomical changes in the crystalline lens concerning its position relative to the cornea. Clinically, the variation in refractive astigmatism caused by accommodative relaxation should be considered when refractive prescription is based on the cycloplegic value.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jcto2040015/s1, Table S1: Autorefraction, keratometry, and ocular residual astigmatism measured pre- and post-cycloplegia; Table S2: Differences in autorefraction, keratometry, and ocular residual astigmatism; Figure S1: Double polar plots for the refractive, keratometric, and ocular residual astigmatism.

Author Contributions: Conceptualization, O.T. and P.M.S.; methodology, A.P. and P.M.S.; software, P.M.S.; validation, O.T., P.M.S. and A.M.B.; formal analysis, P.M.S. and A.P.; investigation, A.P.; resources, A.P.; data curation, A.M.; writing—original draft preparation, A.P. and P.M.S.; writing—review and editing, O.T. and A.M.B.; visualization, P.M.S. and A.M.; supervision, O.T. and P.M.S.; project administration, O.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of Comité Ético para Investigacion Clinica de Badajoz, Spain (approved on 29 March 2022).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to publication of the database in public domain was not accounted in the ethics application.

Acknowledgments: The authors would like to thank OCULUS, Spain, for the technical support provided during the study.

Conflicts of Interest: The authors declare no conflicts of interest.

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