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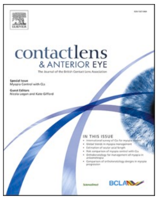

Accommodation response and spherical aberration during 1-Year of orthokeratology lens wear and after discontinuation

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ABSTRACT

Background: To assess accommodation and spherical aberration changes during one year of orthokeratology lens wear and one month after lens cessation.
Methods: A prospective, randomized, longitudinal study was conducted on forty-seven young healthy subjects at the Optometry Clinic of the Complutense University of Madrid (Spain). Non-cycloplegic refraction, high and low uncorrected visual acuity, high and low best corrected visual acuity, accommodative lag, horizontal near phoria, corneal topography, and high-order aberrations were performed at baseline, 1-day, 1-week, 1-, 6- and 12-months of lens wear and after one month of wash out period. $p < 0.05$ was considered as statistically significant.
Results: Spherical equivalent refraction (SE) was −3.23 ± 1.57D at baseline and –0.36 ± 0.64D after 12-months of lens wear, while accommodative lag changed from 0.53 ± 0.39D to 0.15 ± 0.29D after one year of lens wear. No significant differences were found when comparing SE at baseline and after one month of lens cessation ($p > 0.05$). A high correlation was found between the accommodative lag at baseline and after 12 M of lens wear. 22 out of 25 subjects with exophoria at baseline showed a significant reduction in the deviation at 12-months ($p < 0.05$). Total spherical aberration increased during all visits due to the lens wear ($p < 0.05$) although internal spherical aberration showed a significant decrease for 1-week, 1-month and 12-month visits ($p < 0,05$).
Conclusion: Orthokeratology lenses may change the accommodative response of the patient as a reduction on accommodative lag on exophoric patients and an overall increase on the internal spherical aberrations was found during treatment but return to nearly baseline values when cessation.

1. Introduction

Myopia is the most common refractive error worldwide and its increase has been suggested by several authors to be an epidemic [1]. This rise may stem from various factors, including environmental-related lifestyles and potential biological mechanisms influencing refractive errors [2]. A study by Williams et al.[3] investigated the prevalence of myopia in Europe among individuals born during the 20th century. Their analysis revealed a notable increase in myopia rates, rising from 17.8 % to 23.5 % among those born at the start and middle of the 20th century, respectively. The concerning surge in myopia prevalence has also been observed in East Asia. Urban areas report rates exceeding 80 %, whereas, in rural regions, the prevalence is notably lower [4]. Environmental factors related to the ethnic, socioeconomic status level, and lifestyle have been proposed to influence the rising trend of myopia, indicating a potential interaction between genetic predisposition and environmental exposure [1,2].

Nowadays lifestyles, involving activities such as reading, studying, playing with video games and using smartphones can be summarized as excessive near vision activities, which has been proposed as key factors in myopic progression. The correlation between extended near vision activities and myopia has been extensively studied by Gwiazda et al. [5,6]. Their research on myopic subjects uncovered a link between accommodative lag during near vision tasks and prolonged reading. According to the authors, an inadequate accommodative response during near vision activities leads to hyperopic retinal blur, which is believed to be one of the contributing factors to the development of myopia [7]. The accommodative lag theory is based on the hypothesis that an elevated lag in the accommodative response results in a hyperopic retinal blur in the periphery [8], leading to an increase in axial length and consequently myopia.[9]. However, some authors argue that the accommodative lag theory is more a consequence of myopia rather

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than the cause of its progression [10,11]. Therefore, there is disagreement regarding whether the accommodative lag is higher prior to the onset of myopia or if, conversely, it is the development of myopia that causes an increased accommodative lag. Nevertheless, there is agreement that, once myopia is established, there is an increase in accommodative lag values.

Research in myopia control focuses on the use of spectacles or contact lenses that introduce a dioptric addition that minimizes hyperopic retinal defocus [12,13], thereby reducing accommodative lag and, consequently, axial length and myopic progression. Orthokeratology (OK) offers an alternative approach for correcting refractive errors with strong scientific evidence of myopia control efficacy [14]. OK treatment induces changes in corneal shape, flattening the center of the cornea and increasing high-order aberrations (HOAs), such as spherical aberration and coma [15,16]. These changes in corneal aberrations are not directly proportional to the change in internal and total aberrations, with corneal aberrations being higher than internal and total ones. This indicates that although OK lenses only reshape the cornea, changes in internal components of the eye, thus involving the accommodation system (lens and ciliary body), must occur to explain this discrepancy on the total aberrations of the optical system [17–19].

In the context of the relationship between myopia and accommodation, Ding et al.[20] observed a reduction in accommodative lag during OK treatment accompanied by an increase in ocular HOAs increased among children. Similarly, another investigation involving young adults wearing OK demonstrated a relatively diminished accommodative lag [21]; however, neither study evaluated whether changes in accommodation were associated with alterations in internal spherical aberration. While it is stablished that negative spherical aberration increases with accommodation [22,23] none of these investigations were conducted specifically on myopic subjects. Consequently, there remains a gap in understanding the interplay between myopia, accommodation and spherical aberration.

Accordingly, the examination of accommodative and binocular function may shed light on the efficacy of myopia control interventions potentially revealing changes in binocular vision. In this sense, few studies have explored aspects such as eye alignment during OK treatment but up to this point, the findings presented have been inconsistent. For instance, while some studies reported no changes in phoria [24], others noted significant shifts towards exophoria [25–27]. Notably, only the investigation by Song *et al.* was carried out in children.

In view of the above, the main objective of this study was to evaluate the changes in the accommodation response and internal spherical aberration in myopic children and adolescents wearing OK lenses for 12 months and analyze subjects' responses a month after lens cessation. As a secondary objective, and given the relationship between accommodation and eye alignment, phoria changes were also evaluated during OK treatment and after discontinuation.

2. Methods

A 12-month prospective, randomized, longitudinal study was conducted, with a 1-month post-treatment control phase. The inclusion criteria and full methodology were described in Batres et al.[18]. Sixty-four subjects were recruited from the University Clinic of Optometry of the Complutense University of Madrid (Spain) to participate in the study. The study received approval from the Ethics Committee (CEIC) of the San Carlos Clinical Hospital (Madrid, Spain) and all subjects were treated by the tenets of the Declaration of Helsinki revised in 2013 [28]. Informed written consent was obtained from all participants' parents or legal guardians. Participants were informed about the benefits and possible risks of the study before their participation and were free to drop out at any time.

According to manufacturer guidelines, all subjects were fitted with Paragon CRT™ contact lenses (CooperVision, Mesa, AZ) made of HDS 100 material (Paflufocon D, Dk = 100 barrer). Before the prescribed lenses delivery, all subjects received instructions about the wearing schedule, insertion, removal, and care system.

High- and low-contrast corrected and uncorrected distance visual acuity (HC CDVA, LC CDVA, HC UDVA, and LC UDVA respectively), accommodative lag, horizontal near phoria without correction, accommodative convergence over accommodation ratio (AC/A), corneal topography as well as corneal and total wavefront aberrations were assessed. All measurements were systematically repeated three times and conducted by the same experienced examiner (L.B.) at baseline,1 day after the first night of lens wear, between 8:00 and 10:00 am and within three hours after the lens was removed, as well as at 1 week, 1, 6, and 12 months in the afternoon, between 7:00 and 8:00 pm. Measurements were also taken after one month of discontinuing contact lens wear (washout period).

High (100 %) and low contrast (10 %) UDVA and CDVA were performed with the Early Treatment Diabetic Retinopathy Study (ETDRS) test on the VX24 Chart Display (Visionix Ltd., Visionix-Luneau Technologies, Chartres, France) at 4 m under photopic conditions (85 cd/m^2).

To evaluate accommodative response, nott retinoscopy was performed binocularly. The 20/40 line from the ETDRS near chart positioned at 40 cm and the subjective refraction placed in a trial frame. The examiner then determined the accommodative lag or lead by observing the movement of the retinoscopic reflex. Eye alignment was assessed using the alternate cover test, performed at 40 cm with subjects wearing their subjective refraction in a trial frame and looking at a near target (VA 20/40). In case of movement, a prism bar over the right eye was used to neutralize it. Exophoria was annotated as negative values and esophoria as positive values. AC/A ratio was determined by the calculated heterophoria method using the formula: $AC/A = IPD + NFD(Hn - Hd)$, where IPD is the interpupillary distance in centimetres, NFD the near fixation distance in metres (0.4 m), Hn the heterophoria at near vision and Hd the heterophoria at distance. Phoria at near and distance vision was assessed by cover test and the patient wearing their subjective refraction only at baseline and after one month of lens cessation visits.

Two devices were utilized to determine the changes in HOA's: Oculus Pentacam system (Oculus, Wetzlar, Germany) to assess posterior corneal aberration changes and VX110 (Visionix Luneau, France) for anterior corneal and total aberration. The Oculus Pentacam system consists of a rotating Scheimpflug camera that generates 3D images of the anterior segment of the eye during the rotating measurement procedure. During the 2-second measurement, the camera rotates 180° and acquired 25 or 50 images presenting 500 measurement points on the front and back surface of the cornea to draw a true elevation map. Parameters obtained with Pentacam included flat keratometry (flat k), steep keratometry (steep k), and back corneal aberration.

The VX110 is a multi-diagnostic platform that combines Hartmann-Shack based autorefraction and Placido-disk based corneal topography. The Hartmann-Shack measures 1500 points in 0.2 s in an area from 2.0 to 7.0 mm^2. Parameters obtained with VX110 included corneal and total spherical aberration (Z12). All wavefront data from both devices were reported for a 3.0- and 5.0-mm pupil diameter measured up to the sixth Zernike order. The Z12 were evaluated and compared for all visits.

The sample size calculation was determined with the statistical software Granmo 6.0 (Institut Municipal d'Investigació Mèdica, Barcelona, Spain). The normal distribution of the variables was assessed using the Shapiro-Wilk test. Statistical analysis was performed using the SPSS Statistics 23 software (IBM, Chicago, Illinois, USA). For statistical analysis, only one eye of each subject was randomly selected for all variables, except accommodation lag and horizontal near phoria.

To analyse the differences between visits, T-test for related samples and one-way analysis of variance (ANOVA) with Bonferroni correction was performed. Furthermore, the degree of correlation among the different variables between the accommodation lag at baseline and the accommodation lag difference between the baseline and 12 M visits was determined by the Pearson Correlation test. A statistical significance of 95 % was established ($p < 0.05$). Results are shown as mean ± standard deviation.

3. Results

Forty-seven subjects completed full-year follow-up visits (from baseline to 12 M) with an average spherical equivalent refraction (SE) of −3.23 ± 1.57 dioptres (range: −7.75 to −1.00 dioptres). Mean age was 12.43 ± 2.46 years old (range: 8–17 years). Among them, only 42 remained in the study for the one-month after lens cessation visit (-3.23 ± 1.48 dioptres, range: −8.25 to −1.00 dioptres). When asked for their optometric history, 43 participants verbally reported an increase in myopic refractive error two years prior to the start of the study, with twelve of them having two myopic parents. Seven participants were habitual soft contact lens wearers while the remaining forty wore only spectacles.

Table 1 summarizes the different variables under study for baseline and follow-up visits. SE refraction showed a significant decrease after one night of lens wear compared to baseline ($p < 0.001$; T-test for related samples). A statistically significant difference was also observed for all visits except for the visit after one month after dropping out treatment. Keratometry data for both flat and steep corneal meridians showed a significant flattening that was maintained one month after lens wear cessation ($p < 0.001$, ANOVA for related samples). Regarding visual acuity, a statistically significant difference ($p < 0.05$; ANOVA for related samples) was noted between baseline and follow up visits for low contrast CDVA, low contrast UDVA and high contrast UDVA. Significant differences were also observed for high contrast CDVA during the research period ($p = 0.038$, ANOVA for related samples).

The horizontal near phoria and AC/A ratio was only evaluated at baseline, after 1, 6 and 12 months of lens wear and after one month of wash out period (Suppl. Fig. 1). At the onset of the treatment, most of the subjects exhibited exophoria (-3.23 ± 4.95 prismatic dioptres). Of the total subjects, 21 presented orthophoria, 25 exophoria, and one esophoria respectively. Significant differences ($p = 0.003$; ANOVA for related samples) were observed between follow-up visits and baseline measurements for all subjects (Table 1). No significant changes in the near horizontal phoria were found for subjects with orthophoria prior to the orthokeratology treatment. Out of the 21 subjects who started with orthophoria, 18 remained orthophoric through the treatment, while one subject shifted towards exophoria and 2 to towards esophoria. Meanwhile, 22 out of the 25 subjects with exophoria at baseline (-6.24 ± 5.12 prismatic dioptres) showed significant reduction in the deviation at 12 M, ending with a horizontal exophoria of −2.09 ± 3.01 D ($p < 0.05$; T-test for related samples). After one month of dropout, no statistically significant differences were noted compared to baseline, although phoria values were lower than at the onset of the treatment. AC/A ratio showed a significant decrease after one month of OK treatment ($p = 0.019$, T-test for related samples) but not after six months and one year of lens wear ($p > 0.05$, T-test for related samples). Remarkably, AC/A ratio did not return to it original values one month after lens discontinuation but indeed were significantly augmented ($p = 0.029$, T-test for related samples).

Regarding the accommodative response (Fig. 1 and Suppl. Fig. 2), there was a significative decreasing trend in accommodative lag values for all visits from one night in advance compared to baseline ($p < 0.05$; T-test for related samples). Thirty-six out of forty-seven subjects (76.60 %) showed a decrease in the accommodative lag during lens wear, however, no changes or a slight increase were found in eleven participants (23.40 %). These results led to the division of the sample into the lag change group (mean 12.12 ± 2.42 years) and the lag no-change group (mean 13.27 ± 2.53 years). In the lag no-change group, there was a tendency towards an increase in accommodative lag values, with significance observed at the 12 M visit ($p < 0.05$; T-test for related samples). Subjects in the lag change group showed greater accommodative response values at baseline compared to those in the no-change group, being statistically significant ($p < 0.05$; T-test for related samples). No significant differences were found when comparing the washout period values with baseline ($p = 0.221$, T-test for related samples).

Furthermore, a high correlation ($0.8 < r < 1$) was found between the accommodative lag values at baseline and the difference between accommodative lag at baseline and twelve months after lens wear ($p < 0.05$; $r = 0.819$; Pearson correlation test) (Fig. 2 and Suppl. Fig. 3). However, no correlations were found between phoria and accommodative lag with refraction at baseline ($p > 0.05$; $r = 0.152$ and $r = 0.331$, respectively. Pearson correlation test) (Suppl. Fig. 4 and 5).

Table 1

Subjective refraction, visual acuity, keratometry near uncorrected phoria values, AC/A ratio and accommodative lag (means ± SD) after one night (1 N), one week (1 W), one month (1 M), six months (6 M) and twelve months (12 M) of orthokeratology lens wear as well as one month after wash out period (W.Out) compared to baseline.

Variable	Baseline	1 N	1 W	1 M	6 M	12 M	W.Out	p-value
Spherical Equivalent (D^2)	−3.23 ± 1.57	−1.72 ± 1.35	−0.47 ± 0.79	−0.38 ± 0.69	−0.31 ± 0.61	−0.36 ± 0.64	−3.23 ± 1.48	<0.001#
p-value		<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	p = 0.145	
Flat K^3 (mm^4)	7.90 ± 0.21	8.02 ± 0.23	8.17 ± 0.25	8.19 ± 0.26	8.20 ± 0.26	8.21 ± 0.26	7.96 ± 0.21	<0.001#
p-value		<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	
Steep K^3 (mm^4)	7.73 ± 0.23	7.86 ± 0.24	8.03 ± 0.25	8.05 ± 0.25	8.03 ± 0.25	8.02 ± 0.26	7.76 ± 0.23	<0.001#
p-value		<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.001*	
CDVA^5 HC^6 (LogMAR)	−0.04 ± 0.07	−0.03 ± 0.06	−0.05 ± 0.08	−0.04 ± 0.08	−0.05 ± 0.07	−0.06 ± 0.13	−0.09 ± 0.11	0.038#
		0.338	0.691	0.992	0.203	0.348	<0.001*	
CDVA^5 LC^7 (LogMAR)	0.20 ± 0.11	0.35 ± 0.19	0.29 ± 0.17	0.28 ± 0.17	0.32 ± 0.17	0.28 ± 0.17	0.23 ± 0.10	<0.001#
p-value		<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.014*	
UDVA^8 HC^6 (LogMAR)	0.90 ± 0.33	0.46 ± 0.38	0.08 ± 0.2	0.03 ± 0.15	0.03 ± 0.19	0.02 ± 0.16	0.86 ± 0.31	<0.001#
		<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.217	
UDVA^8 LC^7 (Log MAR)	1.08 ± 0.28	0.88 ± 0.40	0.46 ± 0.33	0.37 ± 0.25	0.41 ± 0.44	0.37 ± 0.24	1.14 ± 0.25	<0.001#
p-value		<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.012*	
Near Phoria (Δ^9)	−3.23 ± 4.95	–	–	−2.67 ± 4.64	−1.38 ± 3.26	−1.62 ± 4.21	−2.79 ± 4.31	0.003#
p-value				0.003*	<0.001*	0.005*	0.283	
AC/A[1] ratio	5.74 ± 1.09			5.31 ± 1.31	5.71 ± 0.85	5.52 ± 1.20	6.45 ± 1.24	<0.001#
p-value				0.019*	0.816	0.208	0.029*	
Accommodative Lag (D^2)	0.53 ± 0.38	0.38 ± 0.31	0.34 ± 0.42	0.34 ± 0.43	0.07 ± 0.42	0.15 ± 0.29	0.63 ± 0.36	<0.001#
p-value		0.015*	0.013*	0.022*	<0.001*	<0.001*	0.283	

[1] AC/A accommodative convergence over accommodation ratio ^{2}D dioptres, ^{3}K keratometry, ^{4}mm millimetres, ^{5}CDVA corrected distance visual acuity, ^{6}HC high contrast, ^{7}LC low contrast, ^{8}UDVA uncorrected distance visual acuity, ^{9}Δ prismatic dioptres. *$p < 0.05$ comparison between PRE and the rest of visits; T-test for related samples. #$p < 0.05$; ANOVA for related samples.

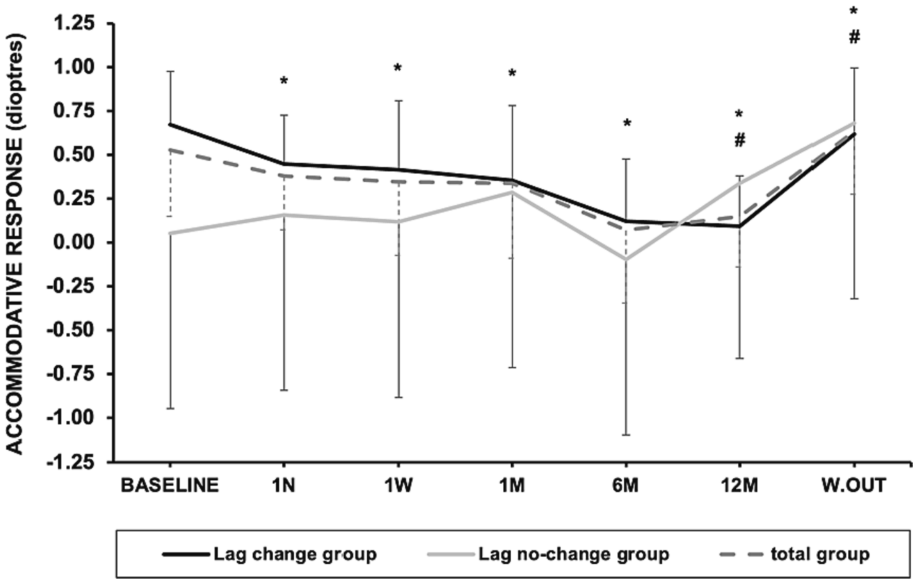

Fig. 1. Accommodative response changes during orthokeratology lens wear. One-year follow up and after one month of wash out period (W.OUT). *$p < 0.05$ on the lag change group compared to baseline. #$p < 0.05$ on the lag no-change group compared to baseline.

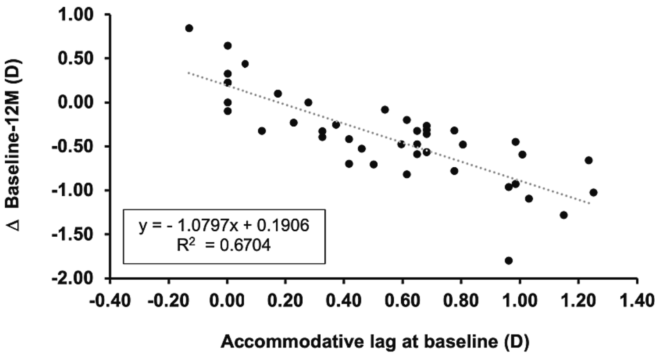

Fig. 2. Correlation between accommodative lag values at baseline and the difference between accommodative lag at baseline and twelve months after lens use (ΔBaseline-12 M).

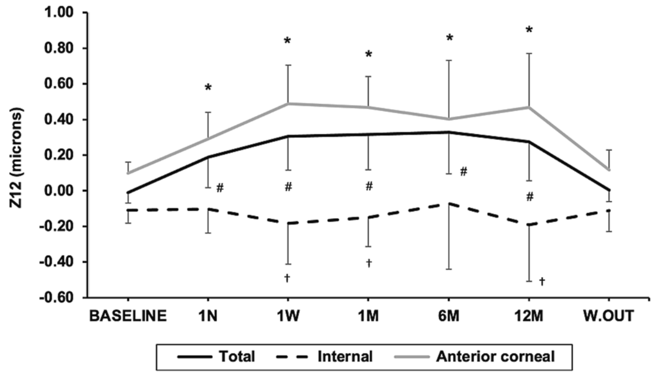

Fig. 3. Total, internal and anterior corneal spherical aberration (Z12) values for 5 mm pupil diameter. * $p < 0.05$ on anterior corneal Z12 when compared to baseline. # $p < 0.05$ on total Z12 when compared to baseline. † $p < 0.05$ on internal Z12 when compared to baseline.

In relation to HOAs computed for 5.0-millimetre pupil diameter, a significant increase was found in 4th order spherical aberration (Z12) values of the corneal anterior surface after one night of lens wear and subsequent visits ($p < 0.05$; ANOVA related samples), as depicted in Fig. 3. Internal spherical aberration, resulting from the subtraction of eye total aberrations minus corneal anterior aberrations, exhibited a significant decrease compared to baseline at one week, one month and 12 months of lens wear visits ($p < 0.05$; ANOVA for related samples). To investigate whether these results may be due to posterior corneal surface or lens changes, corneal posterior spherical aberration was measured with a Scheimpflug Pentacam camera. Statistically significant differences in the Z12 values of the posterior corneal surface, were only observed at the one month visit although without being clinically relevant ($p < 0.001$). A significant increase was noted in the total Z12 values when compared to baseline during follow up visits ($p < 0.05$; ANOVA for related samples). No significant differences were detected in the anterior corneal, posterior corneal, and internal spherical aberration (Z12) values neither considering 3.0- nor 5.0-millimetres pupil diameters, indicating complete reversibility of the reshaping produced by the orthokeratology lenses.

Considering the group classification performed according to the accommodative lag of the participants during the trial, corneal Z12 did not show differences between lag change and no-change groups ($p < 0.05$; ANOVA for related samples). Regarding the lag change group, changes on internal Z12 (Fig. 4) were statistically significant at 1 M, 6 M, 12 M and one month after lens cessation visits when compared to

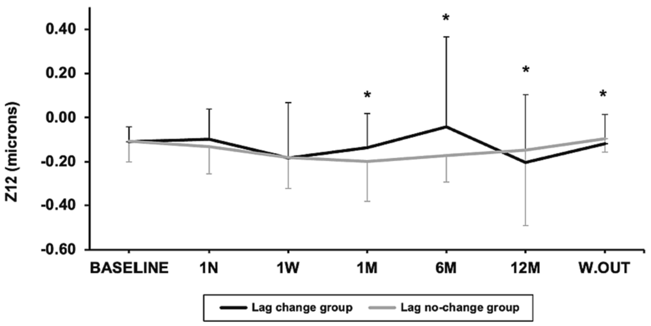

Fig. 4. Differences in internal spherical aberration values (Z12) considering the group classification performed according to the accommodative lag of the participants at baseline (lag change vs lag no-change groups). *$p < 0.05$ on the lag change group when compared to baseline. No significant changes were obtained on the lag no-change group.

baseline ($p < 0.001$, ANOVA for related samples) and throughout the treatment period ($p = 0.027$; ANOVA for related samples). Conversely, these changes were not statistically significant in the lag no-change group at any visit ($p = 0.385$; ANOVA for related samples).

4. Discussion

Numerous studies have previously concluded that an increase in spherical aberration during orthokeratology treatment may elucidate the mechanism of controlling the progression of myopia due to the change in the accommodative system [16,29]. Other studies have evaluated the changes in the accommodative response after OK treatment, showing no agreement on the outcomes. In the present study, a decrease in the accommodative lag was found after one week of lens wear that returned to baseline values after one month of lens cessation, a finding that is in line with those reported by other authors [26,30]. Felipe-Márquez *et al.* [25,31] found no changes during the first three months and three years of OK treatment. Some possible reasons for the lack of agreement on the results could be the different age of the participants and the technique used to measure the accommodative response [32]. More recently, Pereira-da-Mota *et al.* [33] assessed the effects of OK on the accommodative response of myopic subjects during a two-months period. The authors found that the treatment did not affect the accommodative response of adults with low myopic refraction.

The present study found a high correlation between the accommodative lag at baseline and the difference between baseline and 12 M measurements (Fig. 2). This suggests that subjects with greater accommodative lag at baseline may show a larger decrease in their accommodative response, what is in line with results observed by Tarrant *et al.* [34], who proposed that the increase in positive spherical aberration following orthokeratology produce a hypothetical reduction in accommodative lag. Furthermore, a significant increase in internal spherical aberration was found in the accommodative lag change subgroup suggesting that changes in the internal spherical aberration are produced mainly by morphological modifications of the lens.

According to different studies, an increase in accommodative lag among myopic individuals may stem from peripheral hypermetropic defocus, which is linked to an increase in the axial length of the eye and the progression of myopia [5,35,36]. Unfortunately, the results of diverse studies on the accommodative response to OK across different refractive errors have yet to yield a cohesive and definite theory [37,38]. Several trials have proved changes in the magnitude of accommodative lag among orthokeratology contact lens wearers [24–26,30,31], yet consensus regarding the treatment effectiveness on the accommodative response remains elusive. One hypothesis posits a shift in the peripheral refraction [35] while another considers the accommodative response as a complementary mechanism to peripheral refraction. Moreover, it is known that an increase in ocular spherical aberration values may reduce the accommodative lag [26,39]. The outcomes of the present study align with this assertion, since a minor change was found in ocular spherical aberration compared to corneal aberration alongside with an augmented accommodative response. Nevertheless, further investigations are warranted to validate the potential influence of the accommodative response in myopia progression.

After 1 M of washout, accommodative lag reverted to its initial values. Considering accommodative lag as one of the contributing factors to myopia development, it should be monitored alongside axial length over a 6-month period, as recommended by other authors [40,41]. It is noteworthy that accommodative lag can be influenced by spherical aberration. In the unaccommodated eye, the positive spherical aberration of the cornea exceeds the absolute value of the spherical aberration of the lens (negative value). Theoretical calculations have postulated that the combination of negative spherical aberration (found in the accommodated eye), along with the negative defocus (found in the hyperopic image or the accommodative lag) may promote eye growth [42,43]. Furthermore, it has also been shown that OK increases spherical aberration in the positive direction, which theoretically could affect the reduction of the accommodative response [15,17].

In this study, changes in corneal aberrations were obtained on the anterior surface and, although significant aberrometric changes were found on the posterior surface, were not clinically relevant. In agreement with this study, others reported similar results [17,44,45]. However, Owens et al. [46] found a lower flattening after the first week of lens wear which might be associated with slight corneal edema. This study found that the corneal spherical aberration varied more than the total spherical aberration, which might indicate that the difference could be due to lens modification. Joslin et al. [15] have found that total spherical aberration varied significantly compared to corneal spherical aberration after a month of lens wear. However, Chen et al. [19] have found a significant increase in corneal spherical aberration and a proportional increase in total aberration, showing a possible change in internal aberration due to increased negative spherical aberration of the lens. Several studies have described how changes in internal aberration can cause an increase in the accommodative response [17,47]. However, in this study a strong correlation between internal aberration and accommodative lag was not found. More studies should be carried out to measure both parameters with the same device.

HOAs values changed with pupil size. Different studies have shown that the HOAs that change the most with the OK lens is spherical aberration (Z12), followed by the vertical (Z7) and horizontal coma (Z8) [15,17,48]. HOAs values are lower for pupil diameters of 3 mm or less. Consequently, the optical quality of the eye closely resembles a system constrained by diffraction [49] and will increase for pupils bigger than 4 mm. There were statistically significant differences in the value of the spherical aberration of the corneal anterior surface for all follow-up visits compared to baseline, which is in agreement with the results obtained by other authors [17,19,50,51].

After 1-month after lens cessation, total Z12 did not return to the initial values. Berntsen *et al.* [48] observed that total aberrations for 3- and 5-mm pupil diameters seem to stabilize after one month without lenses, except for spherical aberration which continued having fluctuations after that period. An explanation for the difference between these authors' findings may be in the stability of the tear film and the presence of central corneal staining.

According to some authors, to have a near esophoria and wearing monofocal lenses prompts subjects to a greater increase in the myopia progression compared with orthophoric or exophoric children in near vision. [52,53]. Regarding the changes in the phoria during OK, orthophoric subjects showed no changes, however, twenty-two of the twenty-five exophoric subjects were less exophoric during the OK treatment than at the beginning of the study. These results differ from those found by Gifford *et al.* [26,54] and Felipe-Márquez *et al.* [25] who showed, in short term studies, that OK induces a tendency to exophoria in near vision. There are several possible explanations for these disparities, such as the age of the participants, which in the present study was under 17 years old, and the method employed for measuring eye deviation. Different dissociation methods can play a crucial role in comparisons of different tests for near phoria [55]. Nevertheless, the results obtained on the present investigation regarding the AC/A ratio are consistent with the observed increase on accommodative response and the decrease on exophoria. These results are also aligned with the findings of Mutti et al. [56,57] who suggested that an elevated AC/A ratio may serve as an early sign of myopization. Moreover, considering OK treatment as a means for controlling axial length growth [58], it appears that the AC/A ratio is reduced during lens wear period. However, why this decrease on AC/A values do not persist over a 6- or 12-months period is yet to be determined.

Al these aforementioned results support the idea that children with myopia progression have shown greater esophoria in near activities, an increase in accommodative lag, and a greater variability in the accommodative response compared to stable myopia [26]. Therefore, more studies should be carried out in this area. The study has some limitations. Although it would be interesting to have used a control group, this study was based on previous studies where the accommodation does not vary in the control group [24–26]. The authors have considered it more appropriate to compare the baseline and after 1 month of lens cessation with the values in the follow-up visits with the use of OK lenses. Furthermore, binocular vision and accommodation measurements were conducted with trial frames that can have a potential impact as base-in prismatic effects might be induced with the lenses placed at 12 mm rather than on the corneal plane. Another limitation of this study was that total and corneal aberrations were measured with different devices whose repeatability have not yet been assessed; moreover, indirect estimation of internal aberrations might be affected by the abrupt changes in corneal aberrations. Therefore, further studies should be carried out to confirm the results of this study by measuring both spherical aberrations with the same device.

In conclusion, 74 % of the participants of the present study showed a decrease in the accommodative lag during orthokeratology lens wear. The increase in the accommodative response was greater in subjects with higher accommodative lag at baseline. An increase in internal spherical aberration was also found, which along with the accommodative lag change, suggests an effect of the orthokeratology treatment on the accommodative response. Additionally, most variables measured returned to nearly baseline values one month after lens cessation which proof the reversibility of the OK treatment.

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CRediT authorship contribution statement

Carracedo: Conceptualization, Funding, Data curation, Supervision, Writing – review & editing. **Batres:** Conceptualization, Data curation, Writing – review & editing. **Valdes:** Writing – review & editing. **Romaguera:** Writing – review & editing

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