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The Montreal Experience: Impact of Different Orthokeratology Lens Designs on Corneal Treatment Zone Characteristics

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Abstract: OBJECTIVE: To evaluate the effect of the orthokeratology (OK) lens design, used in the Montreal Experience cohort, on corneal treatment zone characteristics and their relationship to the pupil. METHODS: This retrospective study follows previously published work and refers to the analysis of 4 different OK lenses. Tangential topography maps were obtained at baseline and after 1 month of OK lens wear. The extracted parameters are: distance treatment zone diameter (DTZD (mm)); relative peripheral power (RPP (D)); mid-peripheral width (MPW (mm)); a new concept, the plus power ratio (PPR (%)), corresponding to the coverage of the pupil area by the positive power zones. RESULTS: DTZD and MPW were significantly different between the lens designs (Welch's ANOVA). (DTZD (OK 1: 3.68 ± 0.46 mm; OK 2: 3.06 ± 0.67; OK 3: 2.83 ± 0.54; OK 4: 3.20 ± 0.53) MPW (OK 1: 1.65 ± 0.21 mm; OK 2: 1.31 ± 0.40 mm; OK 3: 1.46 ± 0.17 mm; OK 4: 1.57 ± 0.17 mm)). PPR was significantly lower in OK 1 (40.1 ± 22.1%) than the other designs (OK 2: 53.8 ± 18.4%; OK 3: 60.3 ± 13.6; OK 4: 54.7 ± 15.3). CONCLUSION: This study shows that the corneal response to OK lens wear varies with lens design. When analyzed, topographic analysis shows that OK 1 is associated with a larger DTZD, which produces a lower PPR. This may explain why previously published results showed significantly faster axial length (AL) progression with this lens.

Keywords: orthokeratology; myopia management; axial length; pupil diameter

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1. Introduction

Myopia is a refractive error of the eye in which images of distant objects come into focus in front of the retina in the absence of accommodation. This condition prevents the patient from seeing clearly at a distance. Myopia is progressive and can reach an advanced stage associated with a significant risk of ocular pathology [1]. For this reason, special attention has been paid in recent years to the optimization of myopia correction methods in order to adapt them and better control refractive evolution over time.

It has been shown that the quality of the optical signal reaching the retina determines the eye's response to it [2]. Thus, the retina can interpret two types of defocus, either hyperopic or myopic [3]. In both cases, specific biomodulators and growth factors are released, leading to scleral remodeling [4,5]. With prolonged exposure to hyperopic defocus, the sclera becomes softer and the eye tends to elongate, whereas myopic defocus results in greater scleral rigidity and thus resistance to axial length (AL) elongation [5,6]. Accommodation and intraocular pressure are other factors that may modulate this response [7].

Based on the theory of the emmetropization cascade [7], which has been well studied in animal models, changes in axial length have been described as a dose-dependent response to peripheral myopic defocus [8]. In humans, [9] peripheral refraction after orthokeratology (OK) was measured, and its optical effects were shown to produce the aforementioned peripheral myopic defocus. In particular, the effectiveness of OK in controlling myopic

progression appears to be related to the induction of high-order aberrations (HOAs) in the visual system after lens wear. The increase in HOAs results from topographic changes in the cornea from a prolate to an oblate shape. In particular, the effect on ocular growth may be related to the number of spherical aberrations generated by the reshaping of the corneal surface [10]. Specifically, positive spherical aberrations and coma increase progressively during the first week of overnight lens wear [11], but the induced changes may take up to 3 months to stabilize [12]. In addition, the stability of the peripheral refraction induced by OK lens wear was measured over time, and the authors showed that the amount of myopic defocus measured in the first week remained stable over the first year of wear [13].

As reported in a previous article [14], several strategies to increase myopic defocus and related HOAs can be applied and are considered effective, even more so when they are fully customized, taking into account individual and refractive factors that allow for optimization of therapeutic approaches. According to the "Montreal Experience strategy" [14], the type of treatment is selected according to an algorithm based on the specific characteristics of each participant. In this retrospective study, the treatment options were orthokeratology, multifocal soft contact lenses (MSCLs), and low-dose atropine. In general, for low myopia (<-2.50 D) and/or small pupil size (photopic diameter < 4.5 mm as measured with an infrared pupillometer), MSCLs were preferred. For higher myopes (≥ -2.50 D) and/or those with larger pupils (>4.5 mm), OK lenses were usually recommended. Different types of MSCLs or OK lenses were used depending on their availability at the time of dispensing or the personal preference of the practitioner.

Low-dose atropine was used as an adjunct therapy if AL reached or exceeded 26 mm at adulthood based on Tideman's or San Diez growth charts. The final choice of treatment methods was made after discussion with the parents and patients.

All methods used were effective in slowing AL growth and keeping AL progression below the expected progression within a myopic child population. AL progression at 1 year was higher with MSCLs (0.176 mm; 95%CI [0.143, 0.209] and low-dose atropine (0.197 mm; 95%CI [0.144, 0.251]) than with orthokeratology using larger (OK 1) (0.175 mm; 95%CI [0.128, 0.223]) and smaller (OK 2,3,4) (0.102 mm; 95%CI [0.066, 0.139]) treatment zones. In the latter case, this progression was similar to that of emmetropic children.

Having made this observation, it is important to try to understand why there could be such a difference between OK lens designs, even though on paper the lenses could be considered similar since they are based on the same optical principles. It should be noted that OK is a treatment that uses a reverse geometry gas-permeable lens that is worn overnight. It uses the hydraulic forces of the tear film layer to reshape the cornea, temporarily altering the optics of the ocular surface. The modified corneal optics will include a central zone of flattening as well as a zone of reverse curvature forming a midperipheral ring [15,16]. Changes are easily observed with corneal topography. Axial maps provide data on the original corneal shape from which lens parameters are determined, while tangential maps reflect the behavior of the lens on the cornea [17]. The optical effect of these corneal shape changes will be similar to some soft lens bifocal lens designs, except that the plus power generated at the midperiphery will typically be much greater, resulting in greater myopic defocus hitting the peripheral retina, provided the convex power zone is partially contained within the pupil area [18].

It is important to note the differences in lens design to appreciate the potential impact on myopia management. The only real way to analyze the effect of the lens is to study the change in corneal profile induced by the lens. In fact, the same lens designed to compensate for the same dioptric power will behave very differently in two different subjects. Individual parameters such as corneal profile, curvature, eccentricity, Q-value, lid rigidity, sleep position, etc. will impact the final topographic changes. The effect on the progression of myopia can also vary depending on the size of the pupil diameter [18]. Topography is essential to determine the effect of the lens on the eye, its centration and the power changes produced. This was demonstrated in a retrospective study of topographic data comparing the corneal optical effect of two different orthokeratology designs. A

significant difference was found in the central zone, aiming to correct distance vision [19]. It is also possible to achieve the same conclusion by using polynomial mathematical functions [20].

The efficiency of axial length management seems to be influenced by this optical zone difference [21,22]. A larger back optical zone diameter (BOZD) results in a significantly larger treatment zone diameter molded on the cornea, which is associated with higher axial elongation after 2 years of treatment [22]. This article aims to analyze the changes in the corneal profile before and after lens wear in the Montreal Experience orthokeratology cohort using four OK lens designs, in order to better understand the optical differences that led to this efficiency gap found in the Montreal Experience part 1 [14].

2. Materials and Methods

2.1. Study Design and Clinical Population

This is a retrospective study conducted in accordance with the tenets of the Declaration of Helsinki and which was approved by the Ethics Committee Review Board of the Université de Montréal. Following the Montreal Experience part 1, the same dataset of 298 records of patients aged 5 to 18 years who consulted the University of Montreal Myopia Clinic between January 2017 and December 2018 was considered. For the present study, only the OK-treated subjects were analyzed, for a total of 140 patients.

2.2. Orthokeratology Lens Designs

Over the years, 4 different designs of OK or C-OK (customized orthokeratology) lenses were prescribed. Lens parameters are shown in Table 1. At first, the lens selected was based on availability and clinician's preference, and in late 2017 to early 2018, most lenses were customized by software (RGP Designer, Italy, version 1.0).

Table 1. Orthokeratology lens specs (OK: Orthokeratology, C-OK: Customized orthokeratology).

Lens Type	Brand Name	Material	Number of Curves	Back Optic Zone Diameter (mm)	Jessen Factor (D)	Lens Power (D)	Overall Diameter (mm)
OK 1 (OK) (N = 51)	Paragon CRT (Cooper Vision, San Ramon, CA, USA)	Hexafocon A	Four	6.0	0.50	+0.50	10.5
OK 2 (C-OK) (N = 49)	Université de Montréal design (custom; RGP designer software)	Hexafocon A	Six	Variable: Between 5.4 and 6.0 Mean = 5.6	Variable. Mean = 0.75	Variable Mean = +0.75	Variable. Mean = 10.6
OK 3 (C-OK) (N = 18)	DRL (Precilens, Créteil, France)	Hexafocon A	Five	Variable: Between 5.0 and 6.0 Mean = 5.5	1.5	+0.75	Variable. Mean = 10.8
OK 4 (OK) (N = 22)	DreamLens (Bauch &Lomb, Rochester, NY, USA)	Hexafocon A	Five	5.0 to 6.2 Mean = 5.0	0.75	+0.75	10.6

OK lenses differ in design, some of which were originally developed for myopia correction (OK 1 and OK 4), while the other two have designs that have been adapted for myopia management by allowing for more customization (OK 2 and OK 3).

The OK 1 used in this study had a spherical base curve (BC) with a standard BOZD of 6mm. The proprietary "sigmoid proximity" (inverted) curve is a third-order polynomial that connects the base curve to the tangential peripheral curve. The standard overall diameter is 10.5 mm and the lenses are made of Hexafocon A with a Dk of 100 [23]. At the time of the study, peripheral toric curves and/or smaller central zones were not available.

The design of the OK 2 lens was customized using a software developed for this purpose. This allowed the authors to create a lens template in which all parameters could be modified to suit the patient's characteristics. Specifically, the lens is designed with seven curves, and the diameter of the posterior optic zone is selected according to the

pupil size. The reservoir is designed to achieve a minimum of 75 µm and a maximum of 100 µm, regardless of the myopic correction. Thus, it always produces a high level of defocus. Peripheral curves are designed to be toric if the difference in elevation between the two principal meridians along the 8 mm ring was above 20 µm. The lens diameter is determined to cover 95% of the corneal surface, and the curve width is balanced accordingly. If necessary, the sagittal depth of the lens is adjusted with landing zone curves.

The OK 3 design is also customized according to the manufacturer's protocol, which takes into account topographic keratometry values, refraction, and corneal diameter. This unique design includes a second tear reservoir that is formed at mid-distance between the reservoir and the lens edge, by a flattened curve coupled with a steepened curve. This second tear reservoir increases hydrodynamic suction forces, resulting in improved centration and faster epithelial changes. All lens fits were optimized until centration and correct refractive results were achieved. The toric designs, with or without toric posterior optic correction, were used when necessary to achieve the best possible treatment. The OK 3 lenses were manufactured by Hexafocon A. The OK 3 lens design allows for BOZD adjustment.

The OK 4 lens is designed with a posterior optic zone of 6 mm, a fitting curve of 0.6 mm, an alignment zone of 1.0 mm, and a peripheral zone of 0.4 mm, resulting in a standard diameter of 10.6 mm. The tear reservoir is standard as with OK 1 and typically produces a 1:1 ratio of plus power in the midperiphery compared to the myopic correction. This lens is also made of the same 100 Dk material as the previous lenses.

While the lenses vary from patient to patient, the analysis presented here aims to determine a possible relationship between the percentage of the defocus zone that overlaps on the pupillary area and the effect on axial length elongation over the course of a year. This parameter is unique to each patient and does not represent a true comparison of the efficacy of the lens designs per se, but rather their individual impact on the cornea.

2.3. Topographical Assessment

Corneal topography was performed at each visit (Medmont E300 USB, Precision Ophthalmic, Vancouver, BC, Canada). Due to the nature of the clinic, data acquisition was performed by different individuals over the course of the study, but they were trained to use the same methodology according to a standard written protocol. The patient was asked to look at the same target each time, and the images were checked for quality (>95 of the quality index) before interpretation. Centration was also validated, and maps decentered by more than 1 mm from the center of the pupil, vertically or horizontally, were discarded. A minimum of 4 validated maps were taken each time and a composite map was generated. In this study, tangential maps were selected, and all images were analyzed by the main author and double-checked by a second reader (2nd author). Using these maps, the localized radius of each curvature point was calculated with respect to the tangents to those points. This was a representation of the true radius, taking into account the asphericity of the corneal surface. Tangential maps have been recommended for fitting and monitoring OK contact lenses, especially for analyzing the corneal periphery [24]. Participants with analyzable baseline and follow-up topographies were kept for analysis.

The following data were recorded:

Distance treatment zone diameter (DTZD) represents the area where the cornea is flattened, producing a negative (more concave) power on the comparative tangential power map. In this study, the treatment zone was measured in millimeters along the horizontal meridian (Figure 1).

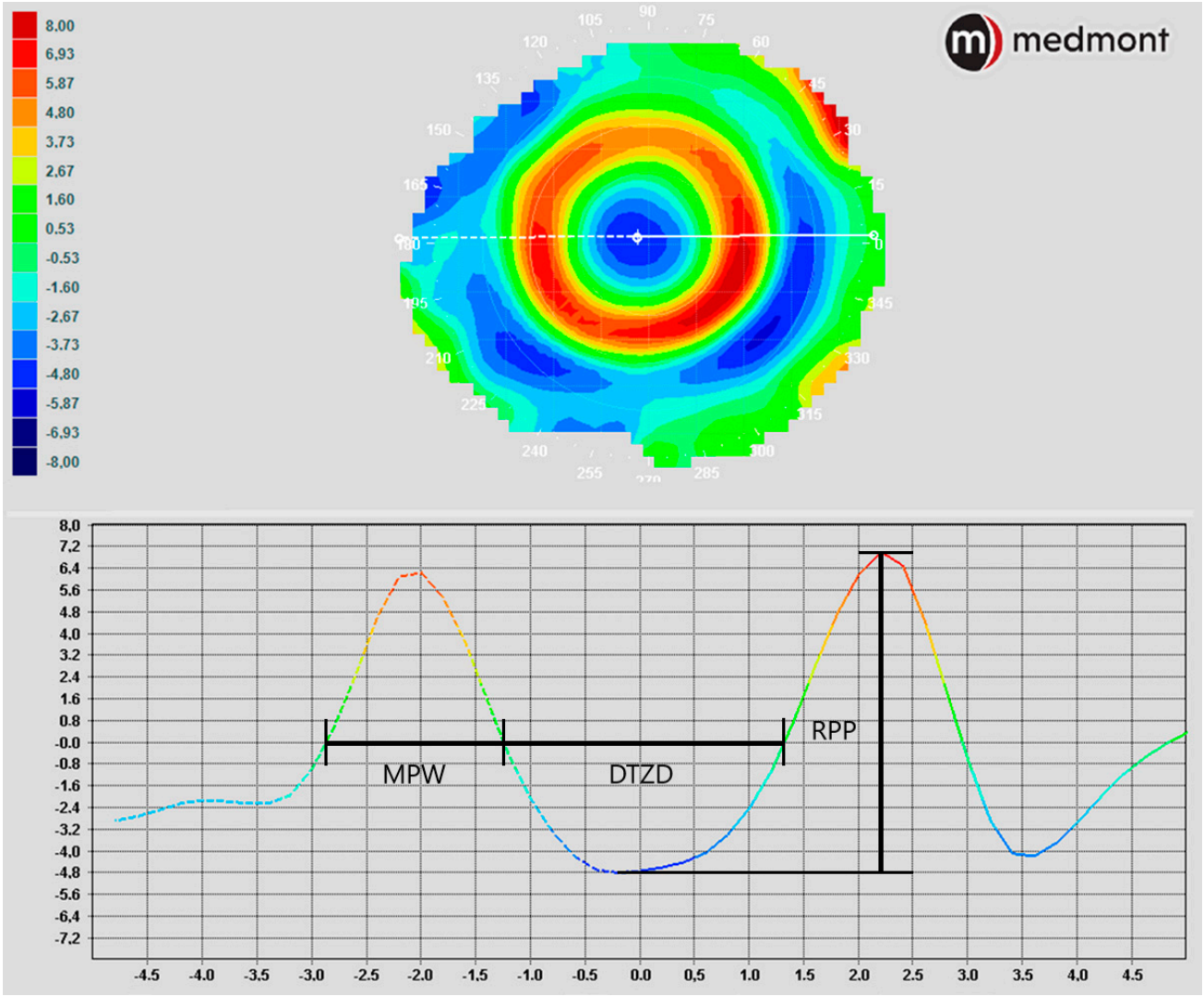

Figure 1. Differential tangential power map, in diopters, showing the impact of a customized OK lens on a cornea and graphical representation of mid-peripheral width (MPW, mm), distance treatment zone diameter (DTZD, mm), and relative peripheral power (RPP, D). Blue describes, in diopter, more negative power difference (corneal flattening) while hotter colors (red-orange) identify where convex power was increased (corneal steepening).

The mid-peripheral width (MPW) is the width of the area of increased curvature that produces a positive (more convex) power on the comparative tangential map, expressed in millimeters.

Relative peripheral power (RPP) represents the difference between the peak of the power curve and the corrected myopia as shown on the differential map (Figure 1), expressed in diopters.

The plus power ratio (PPR) represents the ratio (%) of the area of the proportion of the pupillary area covered by the positive power ring generated in the midperiphery. The pupil size was measured with an infra-red pupillometer (Neuroptics, Irvine, CA, USA) looking at distance under photopic conditions.

Two main formulas are used to calculate the PPR according to the location of the end of the plus power ring created by orthokeratology. If the diameter of the treatment

zone area is greater than the pupil diameter or equivalent, the PPR is calculated using the following formula (Equation (1)):

$$\text{PPR} = 1 - \left(\frac{r_1}{p}\right)^2 \quad (1)$$

r_1 = radius of distance treatment zone diameter
p = radius of pupil diameter

If the diameter of the treatment zone area is smaller than the pupil diameter, the following formula is used (Equation (2)):

$$\text{PPR} = \frac{r_2^2 - r_1^2}{p^2} \quad (2)$$

r_1 = radius of distance treatment zone diameter
r_2 = radius of treatment zone diameter
p = radius of pupil diameter

Parameters described in the equations above are represented in Figure 2.

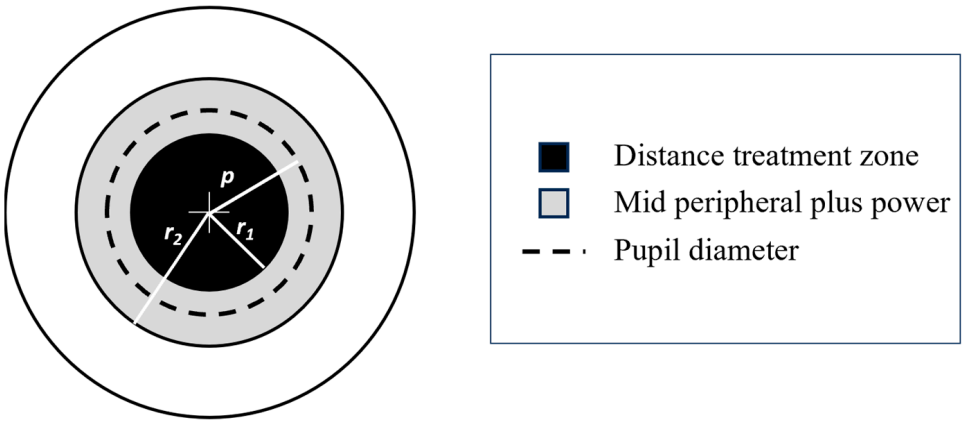

Figure 2. Schematic representation of the plus power ratio component. r_1 represents radius of distance treatment zone diameter, r_2 represents radius of treatment zone diameter and p is the radius of pupils (drawing not to scale).

2.4. Statistical Analysis

Welch's ANOVA test and Games–Howell post hoc tests were performed to compare the 4 orthokeratology lens designs groups for the described parameters (DTZD, MPW, RPP, PPR). All statistical analyses were performed using SPSS version 27.0.1.0 for 64-bit Windows.

3. Results

3.1. Distance Treatment Zone Diameter (DTZD)

Figure 3 shows the DTZD for each lens (OK 1: 3.68 ± 0.46 mm; OK 2: 3.06 ± 0.68 mm; OK 3: 2.83 ± 0.54 mm; OK 4: 3.20 ± 0.57 mm). The distance treatment zone diameter was significantly different between the OK lens designs (F = 19.927, 3) $p < 0.001$, 95%CI = [3.136, 3.331]. Post hoc comparison indicated that OK 1 was significantly different from the 3 other designs used. (OK 1 vs. OK 2; $p < 0.001$, OK 1 vs. OK 3; $p < 0.001$, OK 1 vs. OK 4; $p < 0.001$). The differences in DTZD between OK 1 and OK 2; OK 1 and OK 3; OK 1 and OK 4 were 0.63 mm, 0.85 mm, and 0.48 mm, respectively.

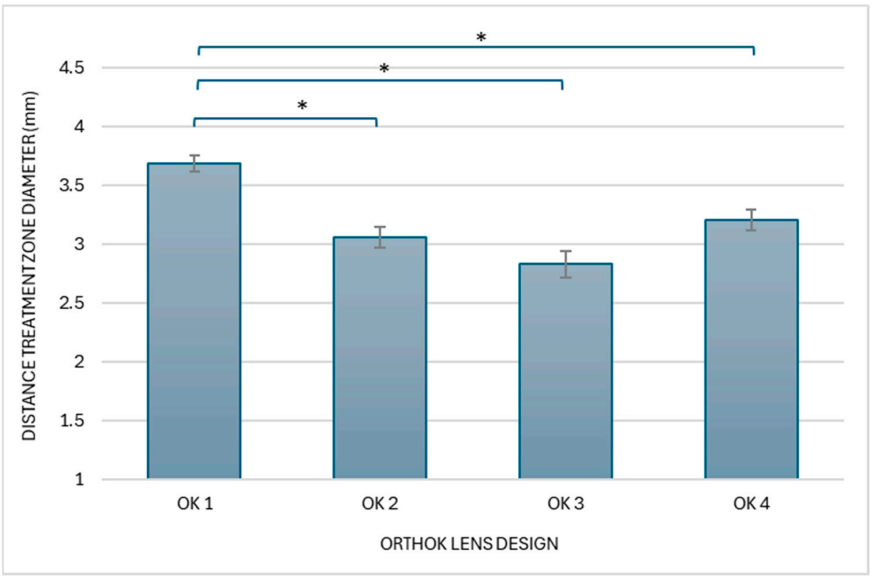

Figure 3. Comparison of the distance treatment zone diameter on the cornea associated with each orthokeratology lens design. Significant differences (*) between OK 1 and OK 2, OK 1 and OK 3, and OK 1 and OK 4.

3.2. Mid-Peripheral Width (MPW)

The MPW mean values were compared according to the four lens designs used (OK 1: 1.65 ± 0.21 mm; OK 2: 1.31 ± 0.40 mm; OK 3: 1.46 ± 0.17 mm; OK 4: 1.57 ± 0.17 mm). (Figure 4). There was a statistical difference between the designs for the mid-peripheral width (F = 12.671, 3) $p < 0.001$, 95%CI [1.44, 1.53], specifically between OK 1 vs. OK 2 (0.336 mm, $p < 0.001$) and OK 1 vs. OK 3 (0.191 mm, $p < 0.001$), OK 2 vs. OK 4 (0.261 mm, $p < 0.001$), and OK 3 and OK 4 (0.116 mm, $p = 0.047$).

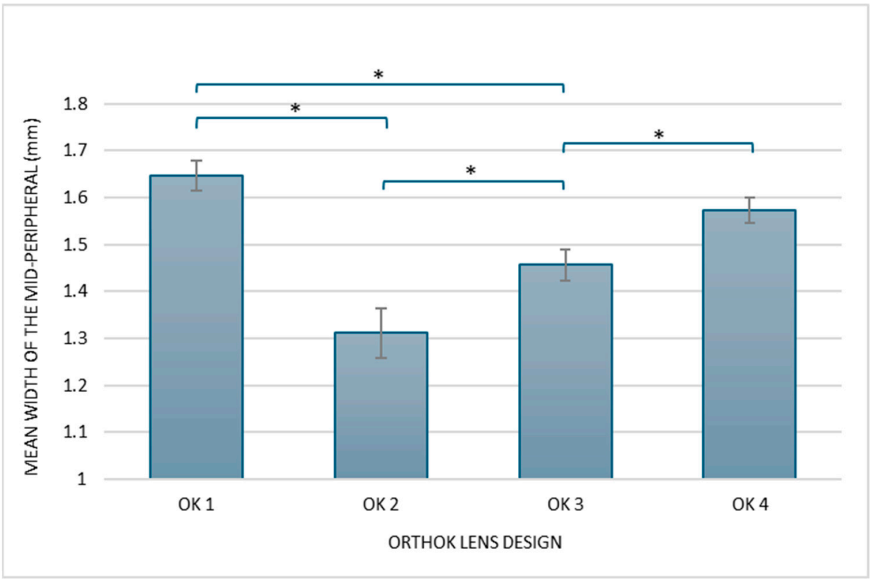

Figure 4. Comparison of the mid-peripheral width on the cornea associated with each orthokeratology lens design. Significant differences (*) between OK 1 and OK 2, OK 1 and OK 3, OK 2 and OK 4, and OK 3 and OK 4.

3.3. Relative Peripheral Power (RPP)

Figure 5 shows the RPP mean for the orthokeratology designs (OK 1: 9.88 ± 2.95 D; OK 2: 9.30 ± 3.80 D; OK 3: 9.91 ± 4.44 D; OK 4: 9.13 ± 3.36 D) (Figure 4). There was no statistically significant difference between the designs (F = 0.547; p = 0.651).

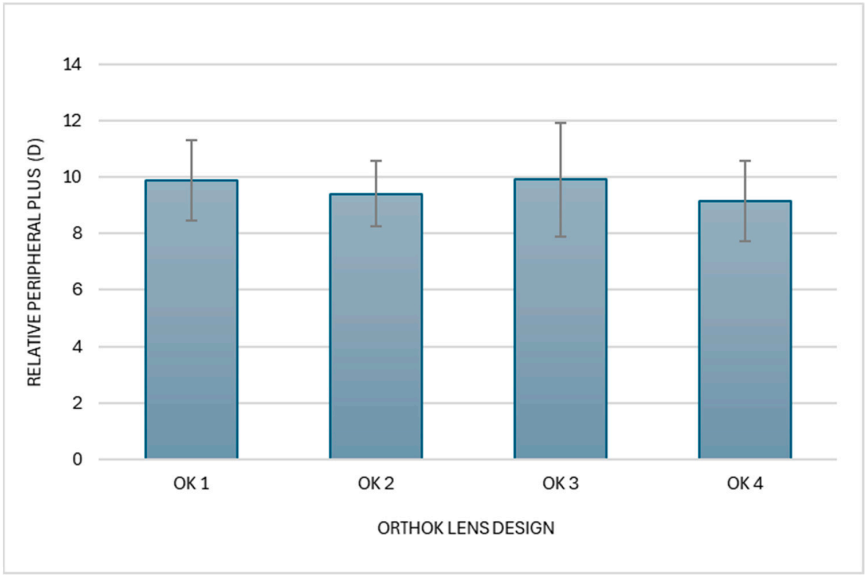

Figure 5. Comparison of the mean relative peripheral plus power on the cornea associated with each orthokeratology lens design. No significant differences between the designs.

3.4. Plus Power Ratio (PPR)

The diameter of the treatment area and the width of the ring of positive power generated at the midperiphery were then related to the participant's pupil size as described above. The relative area associated with each power was measured, and the proportion of positive power within the patient's pupil was determined. When compared, there was a significant difference between the four OK lens designs ((F = 7.761; 3) $p < 0.001$), 95%CI = [48.2, 54.1]. Figure 6 shows that OK 1 is generating a significantly smaller proportion of positive power within the pupil (40.1 ± 22.1%) than the other three designs (OK 2: 53.8 ± 18.4% (p = 0.005); OK 3: 60.3 ± 13.6% ($p < 0.001$); OK 4 54.7 ± 15.3% (p = 0.003)).

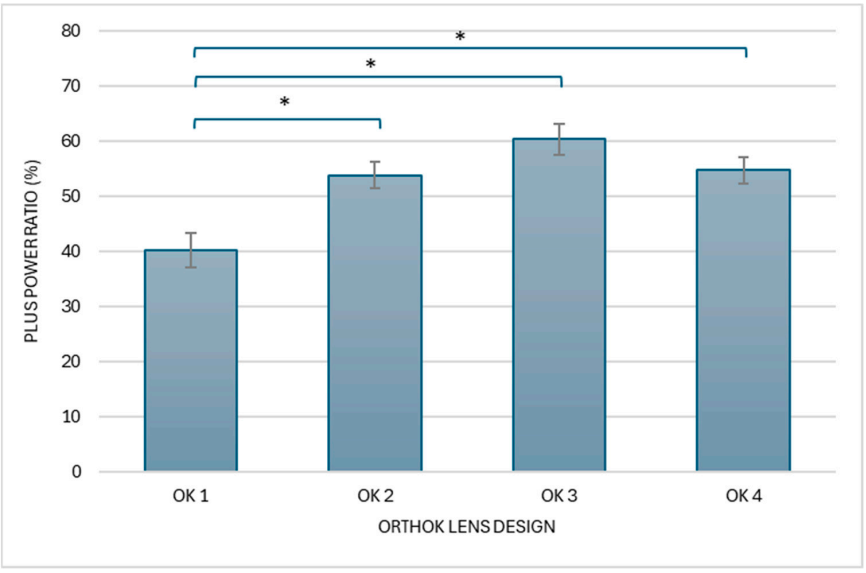

Figure 6. Comparison of the plus power ratio in percentage associated with each orthokeratology lens design. Significant differences (*) between OK 1 and OK 2, OK 1 and OK 3, OK 1 and OK 4.

4. Discussion

This retrospective study shows that different OK lens designs mold the cornea differently and that these differences may be related to the relative progression of the axial length of the eye. Thus, smaller treatment zone diameters on the cornea created by the lenses allow for a larger relative area of myopic defocus in the pupil area. Knowing that there is a dose-response mechanism [21,25], this increase in the area of positive power/myopic defocus in the pupil is likely to result in better control of the axial length progression, which could explain the difference in efficiency found between the large and small BOZD orthokeratology in the Montreal Experience part 1 analysis [14].

The OK corneal molding generates optical defocus from two powers: a first central power, to compensate for the refractive error, and a second, surrounding the central zone, to generate a more convex power associated with myopic defocus. As mentioned above, the myopic and hyperopic defocus signals can be interpreted simultaneously at the retinal level. The proportion of each signal determines the overall direction of refractive development and the effectiveness of a simultaneous optical strategy for myopia management. However, at equal proportions, the myopic defocus tends to be predominant [26,27]. The amplitude of the myopic defocus represents the distance of anterior focal plane in front of the retina. Consequently, a larger dose of myopic defocus will elicit a larger response, resulting in a reduction of axial elongation [28,29].

These two elements make up the "dose" that reaches the retina: the amplitude (power) of the defocus and its relative area of effect on the retina. Another study [25] compared two lenses. The first lens was designed with a larger BOZD and produced a higher amplitude of defocus. The second lens was designed with a smaller central BOZD, which was associated with a lower amplitude of defocus. However, the smaller BOZD lens provided the better axial length management, suggesting that the combination of the two factors (zone diameter and amplitude of defocus generated) may influence the outcome, rather than either of them considered individually.

In the case of this study, the 4 lenses produced similar plus power, approximately 9 D, as measured by RPP variation. If the Montreal experience study shows that the defocus produced by the 4 OK lenses is statistically equivalent, then something else must explain the differences found between the 4 OK lens designs in terms of their effect on axial length. The location of this myopic defocus area must be considered, especially in relation to the pupil. If the myopic defocus area lies outside the pupil, little of this beneficial optical signal will reach the retina, considering the contribution of direct and oblique rays that characterize the entry of light into the eye. On the other hand, if this defocus is partially superimposed on the pupil area, the chances of getting a higher dose of defocus reaching the peripheral macular area (10–20 degrees) and thus positively influencing axial length growth are increased.

However, designing a lens with a smaller BOZD does not automatically translate into an equal variation on the corneal surface. This was previously observed in a study that analyzed the corneal optical effect produced by two different orthokeratology designs [19]. The effect on the corneal surface must be evaluated by analyzing the tangential topographical map, which was performed in this study. OK 1 produced a significantly larger treatment zone compared to the OK 2–3 or 4 designs. The distance treatment zone diameter (DTZD) when wearing OK 2–3 and 4 is considered similar, as no statistically significant differences were found between them. OK 1 is associated with higher AL growth [14]. This finding is consistent with the results of different studies [20,22], reporting better control of axial elongation when a smaller treatment zone is present on the cornea. The width of the area producing this defocus is the second factor to consider. Theoretically, a larger area may contribute to generating a higher dose of defocus, depending on its relationship to the pupil area.

Previous OK studies have explored the effects of either the BOZD diameter or the corneal treatment zone diameter on myopia control. It has been shown that pupil diameter may be important and that better results are obtained when the myopic defocus is partially

within the pupil area [20,21]. However, the relative pupil area covered by the treatment zone has not been previously measured. This study adds new knowledge by introducing the concept of plus power ratio (PPR) in orthokeratology. This concept is important when considering lenses with the same optical zone but producing a different ratio depending on their corneal effect vs. the patient's pupil. For a given optical zone, a larger pupil diameter will increase the PPR, allowing for a greater proportion of myopic to hyperopic defocus, thus contributing to better treatment efficacy, as previously suggested by Chen et al. [18]. In light of this understanding, it is also possible to hypothesize that the better results obtained in some studies combining the use of low-dose atropine and OK lenses may have been obtained in part because of the increase in the dose of defocus affecting the retina as a response to the increase in pupil diameter caused by the drug.

The results from the Montreal Experience part 1 showed a significantly higher AL progression with OK 1 (0.175 mm at year 1/0.359 mm at year 2) than with OK 2, 3, or 4 (0.102 mm/0.249 mm respectively) [14]. When analyzed, OK 1 had a larger treatment zone diameter, resulting in a lower PPR compared to OK 2, 3, and 4. This implies that it may be necessary to consider the patient's pupil diameter/area when selecting OK lens designs and also how this design translates at the corneal level.

The results suggest that the higher ratios are associated with smaller corneal treatment areas, but also with more modest axial length progression. However, the question of the optimal ratio remains, and this retrospective study does not allow us to fully clarify this aspect. The OK 1 lens is not completely ineffective and has a defocus ratio equivalent to 40.1% of the pupil area. Therefore, the minimum threshold to induce a positive effect may be slightly less than 40.1%. Efficacy is improved with other lenses (OK 2–3 and 4) that cover between 53.8 and 60.3% of the pupil without affecting distance vision. Are these the upper limits? Is it possible to increase the coverage even further to achieve greater efficacy? More work is needed to determine these limits, but we can assume that a PPR value between 40% and 60% is associated with increasing efficacy as the percentage of area increases. This is also consistent with the concept of a dose-response at the retinal level.

The results of the chicken and guinea pig studies suggest that the information from the two focal planes depends not only on the amplitude and the sign of the defocus, but also on their relative contrast on the retina. For example, in the chicken study using +10 D/−10 D as bifocal powers, varying the area ratio between the powers also affected the resulting refractive change outcome [26]. In guinea pigs and marmosets, the relative effectiveness of the two powers in controlling axial length appears to be linearly related to the relative lens area associated with each power [30,31]. For example: for +5 D/−5 D powers in the presence of a 50:50 ratio, the eye developed towards hyperopia [31]. In chickens, when the convex power ratio is reduced to 33% for identical powers, the preference for developing hyperopia is completely eliminated and the eyes evolve more toward myopia. In terms of a refractive evolution management, the variation of the PPR would have an effect on the refractive and axial length changes magnitude [26].

It is also important to consider the contrast quality of the retinal image, which is affected by the presence of multiple transition zones. This change in contrast has the potential to affect visual quality enough to induce a mild form of myopia through visual deprivation [32]. Results from four species (chickens, marmosets, guinea pigs, monkeys) [26,27,30,31] showed no evidence that the contrast reduction caused by bifocal lenses causes axial elongation or increased myopia. However, bifocal lenses may reduce best corrected visual acuity compared to single vision lenses. This can be improved either by reducing the amount of myopic defocus or by altering the relative area devoted to the two power zones to change the relative salience of the image planes without changing the diopter interval between the two planes. On the other hand, one must be careful not to decrease the relative area associated with myopic defocus too much, since the AL progression and refractive evolution depends on the size of this area, its value, and its sign. This dose response has been observed in several experimental studies and suggests a greater compensatory effect when there is a larger proportion of myopic defocus area [33–35]. Furthermore, OK

changes not only the corneal profile, but also the high-order aberrations (HOAs). Changes in corneal curvature generate HOAs, especially positive spherical aberration [11,36]. It has been shown that there is a significant association between higher ocular HOA, especially positive spherical aberration, and slower axial growth of the eye in orthokeratology [37].

This study has several biases. First, it is a retrospective study. The results and analysis are dependent on the quality of the data in the patient record. Given the nature of the University Vision Clinic, where multiple stakeholders (students, clinical instructors, residents, faculty) contribute to the case, it remains a challenge to systematically collect clinical data for all patients seen. There is a manual for testing procedures and data collection that all stakeholders must follow, but this does not fully ensure that reliable data are always collected. The fact that all the topographies used in this study were read by the same reader, and cross-checked by a second reader, may compensate for this lack of uniformity at the collection stage.

Second, in the Montreal Experience, treatment modalities are chosen according to patient characteristics, and the approach is therefore fully personalized. Participants were not randomized to a particular treatment modality, nor were they tested for different treatment modalities during the two years of follow-up. However, for the orthokeratology cohort, we analyzed the four designs separately, which limited the choice of treatment bias.

Third, for the AL elongation results from the Montreal Experience [14], it was not possible to retrospectively establish a control group of non-myopic participants matched for age and refractive error. In fact, several tests, including the AL assessment, were not performed systematically in non-myopic patients. Therefore, the use of a historical control group was necessary to put the progression of axial length into perspective in relation to the results obtained with the different OK lenses.

Finally, the results of this study can only be extrapolated to similar populations by using lenses similar to those studied.

5. Conclusions

In this study, we looked at the changes created on the cornea by the four orthokeratology groups in the Montreal Experience cohort showing difference in efficiency. Our results show that it is important to analyze not only the topographies, but also how the lens design translates to the central treatment zone on the cornea. A given optic zone may produce different effects. Analysis of the treatment zone produced on the cornea also enables us to determine a new concept, the plus power ratio, which establishes the percentage of pupil coverage by the defocus zone. It is possible that this ratio will become the benchmark for evaluating the effectiveness of lenses, rather than their characteristics or the level of addition generated. Although the ideal ratio is not known, this study shows that it is higher in the orthokeratology lenses designs creating smaller treatment zone diameter on the cornea.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

Abbreviations List

OK	orthokeratology
C-OK	customized orthokeratology
DTZD	distance treatment zone diameter
RPP	relative peripheral power
PPR	plus power ratio
D	diopters
mm	millimeters
AL	axial length
HOAs	high-order aberrations
MSCL	multifocal soft contact lens
CI	confidence interval
BC	base curve
µm	microns

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