Journal of Optometry (2012) 5, 171–181

View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Universidade do Minho: RepositoriUM

ELSEVIER DOYMA
Journal of Optometry
www.journalofoptometry.org

ORIGINAL ARTICLE

Multi-aspheric description of the myopic cornea after different refractive treatments and its correlation with corneal higher order aberrations

António Queirós[a,*], César Villa-Collar[b], Jorge Jorge[a], Ángel Ramón Gutiérrez[c], José Manuel González-Méijome[a]

[a] Clinical & Experimental Optometry Research Lab-CEORLab. Center of Physics. University of Minho, Braga, Portugal
[b] Clínica Oftalmológica Novovisión, Paseo de la Castellana, Madrid, Spain
[c] Department of Ophthalmology, University of Murcia, Murcia, Spain

Received 18 October 2011; accepted 26 July 2012
Available online 8 September 2012

KEYWORDS
Laser assisted in situ keratomileusis (LASIK);
Corneal asphericity;
Corneal aberrations;
Corneal refractive therapy

Abstract
Background: To analyse the asphericity of the anterior corneal surface (ACS) for different diameters, and correlate those values with corneal higher order aberrations (cHOA) before and after myopic treatments with corneal refractive therapy (CRT) for orthokeratology and customized (CL) and standard laser (SL) assisted in situ keratomileusis (LASIK).
Setting: Clínica Oftalmológica NovoVisión, Madrid, Spain.
Methods: The right eyes of 81 patients (27 in each treatment group), with a mean age of 29.94 ± 7.5 years, were analysed. Corneal videokeratographic data were used to obtain corneal asphericity (Q) for different corneal diameters from 3 to 8 mm and cHOA root mean square (RMS) obtained from Zernike polynomials for a pupil diameter of 6 mm.
Results: There were statistically significant differences in asphericity values calculated at different corneal diameters for different refractive treatments and their changes. The difference between asphericity at 3 and 8 mm reference diameters showed statistically significant correlations with spherical-like cHOA that was also significantly increased after all procedures.
Conclusions: The shift in corneal asphericity and the differences among different treatment techniques are more evident for the smaller reference diameters. These differences can be much reduced or even masked for a peripheral reference point at 4 mm from centre, which is used by some corneal topographers.
© 2011 Spanish General Council of Optometry. Published by Elsevier España, S.L. All rights reserved.

* Corresponding author at: Department of Physics (Optometry), Campus Gualtar, University of Minho, 4710-057 Braga, Portugal.
E-mail address: aqp@fisica.uminho.pt (A. Queirós).

1888-4296/$ – see front matter © 2011 Spanish General Council of Optometry. Published by Elsevier España, S.L. All rights reserved.
http://dx.doi.org/10.1016/j.optom.2012.08.002

PALABRAS CLAVE
Queratomileusis in situ assistida por laser excimer (LASIK);
Asfericidad corneal;
Aberraciones corneales;
Terapia refractiva corneal

Descripción multi-asférica de la córnea miópica tras diferentes tratamientos refractivos y su correlación con las aberraciones corneales de alto orden

Resumen

Antecedentes: Analizar la asfericidad de la superficie corneal anterior (SCA) para diferentes diámetros, y correlacionar dichos valores con las aberraciones corneales de alto orden (cHOA) antes y después de tratamientos miópicos con terapia refractiva corneal (TRC) para ortoqueratología y LASIK personalizado y estándar.

Centro: Clínica Oftalmológica NovoVisión, Madrid, España.

Métodos: Se analizaron los ojos de 81 pacientes (27 en cada grupo de tratamiento), con una edad media de 29,94 ± 7,5 años. Se utilizaron los datos videoqueratográficos para obtener la asfericidad corneal (Q) para diferentes diámetros corneales, de 3 a 8 mm, y el error cuadrático medio de las cHOA caracterizadas mediante los polinomios de Zernike para un diámetro de pupila de 6 mm.

Resultados: Se obtuvieron diferencias estadísticamente significativas en cuanto a los valores de asfericidad calculados con diferentes diámetros corneales para diferentes tratamientos refractivos y para sus cambios tras el tratamiento; asimismo la diferencia entre la asfericidad para los diámetros de referencia de 3 y 8 mm mostró unas correlaciones estadísticamente significativas con las cHOA spherical-like, que experimentaron un incremento considerable con posterioridad a todas las intervenciones.

Conclusiones: El cambio en la asfericidad corneal y las diferencias entre las diferentes técnicas de tratamiento es más evidente para los diámetros de referencia más pequeños. Dichas diferencias pueden ser reducidas mucho más, e incluso enmascararse, para un punto de referencia periférico a 4 mm de distancia del centro, el cual es utilizado por algunos topógrafos corneales.
© 2011 Spanish General Council of Optometry. Publicado por Elsevier España, S.L. Todos los derechos reservados.

Introduction

Laser-assisted in situ keratomileusis (LASIK) and CRT for orthokeratology are two techniques that attempt a complete independence from conventional compensation as spectacles or traditional contact lenses in myopic patients.[1–3] Both techniques use a similar principle to achieve myopia correction, flattening the anterior corneal surface (ACS), thus reducing the total power of the eye but they are substantially different in the way they produce such effect. LASIK removes stromal tissue while CRT does a redistribution of the corneal tissue. In both cases the peripheral cornea is supposed to remain unchanged.[4]

There is an increase in corneal asphericity, changing from its initially prolate shape ($Q < 0$) to an oblate contour ($Q > 0$), being flatter in the centre than in the paracentral zone surrounding the treatment area.[1,5–8] However even if the ACS has been classically defined by a unique value of corneal asphericity, or two values corresponding to the orientations of the two principal meridians,[9] corneal asphericity changes significantly depending on the peripheral reference points. An evidence of this is the different values of Q that can be obtained in the same individuals using different corneal topographers. In a previous study we have observed those differences in Q values for different reference diameters and the different shift of Q values from the more central to the more peripheral reference points according to the corneal astigmatism.[10] It is also expected that these multi-aspheric concept of the cornea can also differ significantly depending on the corneal refractive treatment being performed.

With the development of techniques for measuring the optical quality of the eye, several studies have allowed a better knowledge of the optical quality of the corneal surface after LASIK[3,11,12] or orthokeratology.[13,14] Both refractive techniques significantly increase the ocular higher order aberrations,[1] particularly third and fourth order aberrations.[13,15,16]

Alterations in corneal asphericity and the corresponding increase in optical aberrations have a significant impact not only in the quality of vision,[17] but also on contrast sensitivity[12,14] and other visual functions as night vision disturbances.[3]

Since the treatment zone varies according to treatment technique and the cornea's response to the different correction procedures,[4,18] and because the cornea possesses different degrees of asphericity according to the corneal zone being analysed,[10] it is important to study asphericity values for different corneal diameters in order to fully characterise this important property that defines the post-surgical corneal contour and evaluate its impact on the higher order aberrations induced as a consequence of such changes.[19] Furthermore, Patel's analysis of the corneal shape within the apical zone of operated eyes and normal eyes suggests that the corneal contour would be better defined using different conic sections with different shape factors depending on the corneal region to be represented.[20]

Thus, the purpose of this study was to evaluate corneal asphericity for different corneal diameters after refractive treatments (CRT, LASIK SL and LASIK CL), as well as to correlate these values with corneal high order aberration (cHOA). To the best of our knowledge, this is the first report characterizing the multi-aspheric description of the cornea after surgical and non-surgical corneal refractive interventions for myopia correction.

Materials and methods

Subjects and inclusion criteria

The clinical records of 81 patients submitted to corneal refractive therapy (CRT, $n = 27$), standard LASIK (SL, $n = 27$) and customized LASIK (CL, $n = 27$) at the Clínica Oftalmológica Novovisión, (Madrid, Spain) have been retrospectively evaluated. Mean age was 29.94 ± 7.5 years (ranging from 14 to 49), of which 50 were female (61.7%) and 31 were male (38.3%). Only patients with myopia between −0.75D and −4.25D and astigmatism below −1.75D were included in order to match the range of treatments more commonly used with CRT. No patient suffered from ocular disease or had been submitted to previous ocular surgery. Complete optometric and ophthalmological examinations were performed before surgical and non-surgical correction of myopia through the aforementioned techniques. A minimum of 3 months was required to guarantee that the topography was completely stable.[21,22] After that, the patients should have demonstrated to be successfully treated with respect to residual refractive error ($\leq \pm 0.50$D), visual acuity ($\geq$20/20 or higher uncorrected visual acuity), surface regularity and centring of the treatment zone (below 0.5 mm of decentration) before being elected for this study. Another important inclusion criterion was that the videokeratoscope examinations had been performed between 4:00 and 8:00 P.M. to minimize the influence of diurnal variations in corneal thickness[23] that might potentially influence anterior corneal topography.[24]

This study followed the tenets of the Declaration of Helsinki. Informed consent was obtained from all patients before all the interventions and they also gave their consent to treat their data anonymously for research purposes.

LASIK surgery

In all cases the ablation was central, with an optic zone of 6.50 mm for all LASIK treatments. A transition zone of 0.30 mm for the spherical cases in the SL group and 1.25 mm for astigmatic corrections and CL procedures was used.

Surgical routine for LASIK surgery was held according to international standards, and the commonly accepted criteria for refractive surgery procedures were observed with regards to predictability, efficacy and safety. After creating a 120 μm, 9.5 mm diameter flap with a Hansatome microkeratome (Chiron Vision, model 2765; Bausch & Lomb, Claremont, CA, USA), SL (Munnerlyn based) and CL (topography based) ablation profiles were produced using the Allegretto Wave Eye-Q – 400 Hz – (Wavelight, Erlangen, Germany). All surgical procedures were uneventful and successful.

Corneal refractive therapy: lens characteristics

Paragon CRT (paflufocon D, Dk = 100 barrer) sigmoid reverse geometry rigid gas permeable lenses were used (Paragon Vision Sciences, Mesa, AZ, USA). Trial lenses were derived from sliding table monograms provided by the manufacturer and which have shown high levels of predictability in terms of first trial success.[25] Fitting was evaluated according to the recommendations of the manufacturer regarding fluorescein pattern, topographical evaluation, refractive and visual outcomes.

Calculations of *Q* values and corneal monochromatic cHOA from corneal topography

Topographic data were obtained using the Atlas Mastervue videokeratoscope (Humphrey Zeiss Instruments, San Leandro, CA, USA). The corneal topographer was calibrated before data acquisition according to the manufacturer's recommendations. Corneal videokeratographic data were downloaded onto floppy disks in ASCII file format, which contained information about corneal elevation, curvature, power and position of the pupil.

The *Q*-value was calculated for different corneal chord diameters: 3.0 mm (Q_3), 4.0 mm (Q_4), 5.0 mm (Q_5), 6.0 mm (Q_6), 7.0 mm (Q_7) and 8.0 mm (Q_8) using the calculations feature of Vol-CT 6.89 software (Sarver & Associates, Inc., Carbondale, IL, USA).

cHOA were expressed as Zernike polynomials Z_3^{-3} to Z_6^6 which comprise front corneal surface aberrations up to the sixth order using the calculations modes of Vol-CT 6.89 software (Sarver & Associates, Inc., Carbondale, IL, USA) using as a reference point the centre of the pupil. Total cHOA root mean square (RMS) (including Zernike polynomials Z_3^{-3}, Z_3^{-1}, ..., Z_6^4, Z_6^6) and RMS values for 3rd, 4th, 5th and 6th order, spherical-like aberrations (including Zernike polynomials Z_4^0 and Z_6^0), coma-like aberrations (including Zernike polynomials Z_3^{-1}, Z_3^1, Z_5^{-1} and Z_5^1) were calculated. All aberrations were calculated for a pupil diameter of 6 mm.

Statistical analysis

The SPSS software package v.16 (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. Kolmogorov–Smirnov Test was applied in order to assess normality of data distribution. Kruskal–Wallis Test or ANOVA (Bonferroni post hoc test) for non-normally or normally distributed variables, respectively, was performed to evaluate whether statistically different values were present among the clinical groups of SL, CL and CRT. When normality could not be assumed, Wilcoxon Signed Ranks Test was used for paired comparison between techniques and Paired Samples Test was used when normality could be assumed for pair comparisons between treatments. Bivariate correlation analysis was used to evaluate potential correlations between differences in cHOA and *Q* for different corneal diameters. When normality could be not assumed, Spearman correlation was used; Pearson correlation was used when normality could be assumed. For statistical purposes, a *p* value lower than 0.05 was considered statistically significant.

Results

Baseline demographic characteristic

Table 1 shows the pre-treatment demographic data for each group including mean values, standard deviation, maximum and minimum values. No statistically significant

Table 1 Demographic characteristics (mean, S.D., maximum and minimum) of the population under evaluation before the treatment in each group: standard LASIK, custom LASIK and Corneal Refractive Therapy.

	SL ($n=27$) mean ± SD max/min	CL ($n=27$) mean ± SD max/min	CRT ($n=27$) mean ± SD max/min	p
Gender (female/male)	21/6	12/15	17/10	
Age (years)	32.30 ± 5.79	31.07 ± 5.33	26.44 ± 9.67	
	23/48	25/43	14/49	
Time interval (months)	5.04 ± 2.31	5.28 ± 1.83	3.79 ± 1.42	
	3.00/9.63	3.00/8.23	3.00/8.93	
M (D)	−2.82 ± 0.77	−2.82 ± 0.79	−2.82 ± 0.78	0.998[¥]
	−4.25/−1.63	−4.38/−1.50	−4.38/−1.63	
J_0 (D)	0.23 ± 0.41	0.11 ± 0.22	0.15 ± 0.29	0.406[¥]
	−0.65/0.88	−0.25/0.74	−0.47/0.86	
J_{45} (D)	−0.01 ± 0.17	−0.03 ± 0.17	−0.03 ± 0.16	0.971[¥]
	−0.48/0.38	−0.63/0.43	−0.40/0.37	
RMS_{3rd}	0.342 ± 0.290	0.299 ± 0.122	0.322 ± 0.203	0.873[¥]
	0.111/1.495	0.172/0.599	0.089/1.121	
RMS_{4th}	0.291 ± 0.120	0.255 ± 0.071	0.291 ± 0.156	0.392[¥]
	0.152/0.683	0.158/0.488	0.124/0.899	
RMS_{5th}	0.143 ± 0.205	0.135 ± 0.081	0.128 ± 0.124	0.406[¥]
	0.034/1.096	0.014/0.314	0.031/0.552	
RMS_{6th}	0.093 ± 0.099	0.091 ± 0.064	0.086 ± 0.073	0.748[¥]
	0.020/0.480	0.019/0.320	0.019/0.340	
RMS_{Total}	0.504 ± 0.354	0.438 ± 0.140	0.478 ± 0.263	0.931[¥]
	0.280/2.033	0.287/0.772	0.255/1.576	
$RMS_{Spherical}$	0.204 ± 0.088	0.160 ± 0.073	0.216 ± 0.089	0.039[*]
	0.043/0.359	0.044/0.288	0.033/0.415	
RMS_{Coma}	0.240 ± 0.169	0.258 ± 0.111	0.260 ± 0.155	0.369[¥]
	0.035/0.690	0.090/0.562	0.055/0.643	
$RMS_{S.Astg}$	0.113 ± 0.134	0.112 ± 0.093	0.096 ± 0.075	0.954[¥]
	0.011/0.677	0.011/0.344	0.027/0.349	
Q_3	−0.29 ± 0.14	−0.29 ± 0.14	−0.26 ± 0.14	0.661[*]
	−0.71/−0.07	−0.57/−0.03	−0.55/−0.01	
Q_4	−0.30 ± 0.13	−0.30 ± 0.14	−0.27 ± 0.14	0.667[*]
	−0.62/−0.06	−0.59/−0.05	−0.57/−0.03	
Q_5	−0.31 ± 0.12	−0.32 ± 0.13	−0.28 ± 0.14	0.484[¥]
	−0.58/−0.05	−0.58/−0.07	−0.56/−0.04	
Q_6	−0.31 ± 0.12	−0.33 ± 0.13	−0.29 ± 0.14	0.447[*]
	−0.59/−0.05	−0.57/−0.10	−0.55/−0.07	
Q_7	−0.32 ± 0.12	−0.35 ± 0.12	−0.30 ± 0.14	0.354[*]
	−0.61/−0.05	−0.55/−0.12	−0.58/−0.09	
Q_8	−0.34 ± 0.13	−0.37 ± 0.13	−0.31 ± 0.14	0.279[*]
	−0.64/−0.05	−0.59/−0.15	−0.60/−0.12	

SL, standard LASIK; CL, custom LASIK; CRT, corneal refractive therapy; RMS, root mean square higher order aberrations; Q, asphericity.
[*] ANOVA.
[¥] Kruskal Wallis Test.

differences were found for the initial mean spherical equivalent refraction among the three clinical groups ($p = 0.998$, Kruskal–Wallis Test).

Corneal high order aberrations (cHOA)

Fig. 1 shows the RMS values for higher order aberrations after treatment in the three groups. RMS values for 4th-order, 6th-order, total RMS, spherical aberration and coma were significantly different among the three groups, with CRT showing the higher values. There were no statistically significant differences between the three groups for the 3rd-order, 5th-order RMS and secondary astigmatism. Overall, there has been only difference in pair comparison CL vs CRT and SL vs CRT for 4th, total, spherical aberration (sph) and coma RMS.

The differences between pre and post-refractive surgery procedures and CRT are illustrated for cHOA RMS in Fig. 2. Statistically significant differences were found between the differences in the three techniques for fourth order aberrations ($p < 0.001$, ANOVA), total RMS ($p < 0.001$, Kruskal–Wallis

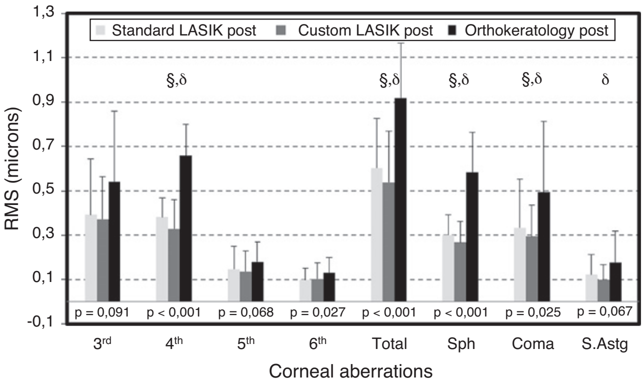

Figure 1 HOA RMS for the three different groups after refractive interventions for a 6-mm pupil. Bars represent standard deviation (SD). Significance values correspond to the comparison of the three clinical groups (Kruskal Wallis Test). Comparison of pair of treatments: θ for statistically significant differences between SL and CL; § for statistically significant differences between SL and CRT and δ for statistically significant differences between CL and CRT.

Test), spherical-like RMS ($p < 0.001$, ANOVA) and coma-like RMS ($p = 0.016$, ANOVA). Conversely, no differences were found between the different techniques for third, fifth and sixth order aberrations, as well as for secondary astigmatism.

Asphericity at different corneal diameters (*Q*)

Fig. 3 shows the post-surgical values of *Q* at different corneal diameters. Post-surgical *Q* values were statistically different between these three treatments with most positive values being found for CRT. We also separately compared SL with CL and found no statistically significant differences between them, either in the calculation of post-treatment aberrations ($p > 0.093$, *t*-test) or for the *Q* values for different

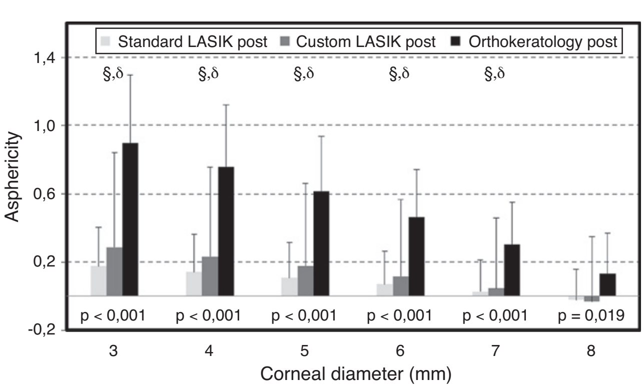

Figure 2 Differences in values of RMS (post−pre) for HOA in the three different groups after refractive interventions for a 6-mm pupil. Bars represent standard deviation (SD). Significance values correspond to the comparison of the three clinical groups (*ANOVA and ¥Kruskal Wallis Test). Comparison of pair of treatments: θ for statistically significant differences between SL and CL; § for statistically significant differences between SL and CRT and δ for statistically significant differences between CL and CRT.

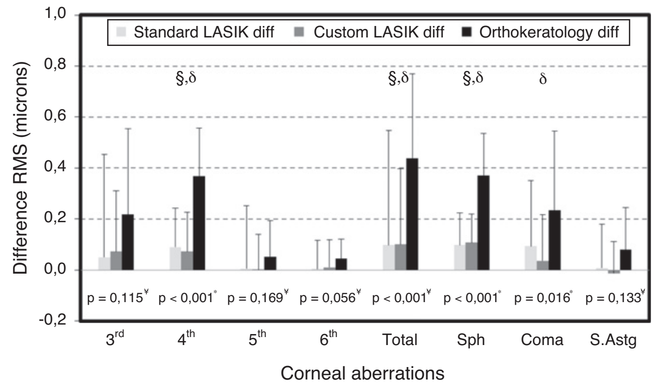

Figure 3 Asphericity at different corneal diameters after refractive interventions. Bars represent standard deviation (SD). Significance values correspond to the comparison of the three clinical groups (Kruskal Wallis Test). Comparison of pair of treatments: θ for statistically significant differences between SL and CL; § for statistically significant differences between SL and CRT and δ for statistically significant differences between CL and CRT.

diameters ($p > 0.117$, Mann−Whitney Test). In comparison pair-by-pair, only for 8 mm diameter no statistical significant differences were found.

The differences between pre and post-refractive surgery procedures and CRT are illustrated for *Q* at different corneal diameters in Fig. 4. The differences in *Q* after the intervention at different corneal diameters were statistically significant among the clinical groups, except for the asphericity obtained at 8 mm.

Table 2 shows mean values, standard deviation and the value of statistical significance for differences (post−pre) in cHOA and corneal *Q* after SL, CL and CRT treatments. In all three cases we can observe the increase in values of cHOA being statistically significant in the three interventions for the values of fourth order RMS and spherical-like

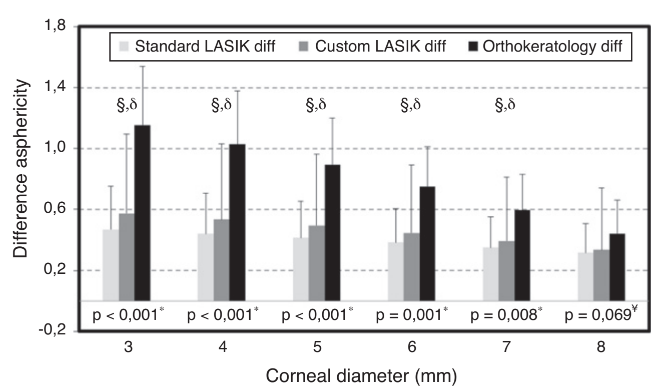

Figure 4 Differences in values of asphericity (post−pre) at different corneal diameters after refractive interventions. Bars represent standard deviation (SD). Significance values correspond to the comparison of the three clinical groups (*ANOVA and ¥Kruskal Wallis Test). Comparison of pair of treatments: θ for statistically significant differences between SL and CL; § for statistically significant differences between SL and CRT and δ for statistically significant differences between CL and CRT.

Table 2 Differences between alterations in HOA and asphericity for different diameters (post-minus pre-intervention) after each refractive intervention and their statistical significance (values of RMS are expressed in microns).

△ (Post−pre)	SL		CL		CRT		§-SLvsCRT δ-CLvsCRT
	Mean ± SD	p	Mean ± SD	p	Mean ± SD	p	
ΔRMS_{3rd}	0.051 ± 0.404	0.156¥	0.073 ± 0.237	0.212¥	0.217 ± 0.337	0.002¥	
ΔRMS_{4th}	0.090 ± 0.152	0.001¥	0.073 ± 0.155	0.014¥	0.368 ± 0.189	<0.001¥	§, δ
ΔRMS_{5th}	0.006 ± 0.246	0.068¥	0.003 ± 0.139	0.923¥	0.052 ± 0.141	0.007¥	
ΔRMS_{6th}	0.005 ± 0.111	0.171¥	0.011 ± 0.108	0.866¥	0.045 ± 0.076	0.003¥	
ΔRMS_{Total}	0.099 ± 0.448	0.021¥	0.101 ± 0.296	0.124¥	0.439 ± 0.330	0.000¥	§, δ
$\Delta RMS_{Spherical}$	0.098 ± 0.126	<0.001*	0.108 ± 0.113	<0.001*	0.369 ± 0.166	<0.001*	§, δ
ΔRMS_{Coma}	0.094 ± 0.257	0.041¥	0.037 ± 0.181	0.280¥	0.236 ± 0.308	0.001¥	δ
$\Delta RMS_{S.Astg}$	0.009 ± 0.170	0.337¥	−0.012 ± 0.124	0.581¥	0.080 ± 0.166	0.020¥	
ΔQ_3	0.469 ± 0.282	<0.001*	0.573 ± 0.521	<0.001¥	1.154 ± 0.385	<0.001*	§, δ
ΔQ_4	0.441 ± 0.265	<0.001*	0.534 ± 0.498	<0.001¥	1.029 ± 0.349	<0.001*	§, δ
ΔQ_5	0.414 ± 0.241	<0.001*	0.494 ± 0.470	<0.001¥	0.895 ± 0.304	<0.001*	§, δ
ΔQ_6	0.384 ± 0.220	<0.001*	0.447 ± 0.444	<0.001¥	0.750 ± 0.263	<0.001*	§, δ
ΔQ_7	0.350 ± 0.202	<0.001*	0.394 ± 0.420	<0.001¥	0.597 ± 0.234	<0.001*	§, δ
ΔQ_8	0.316 ± 0.192	<0.001*	0.335 ± 0.404	<0.001¥	0.443 ± 0.219	<0.001*	

SL, standard LASIK; CL, custom LASIK; CRT, corneal refractive therapy; RMS, root mean square higher order aberrations; Q, asphericity. Comparison of pair of treatments: CL and SL no statistically significant differences for any parameter; § for statistically significant differences between SL and CRT and δ for statistically significant differences between CL and CRT.

* Paired samples test.

¥ Wilcoxon signed ranks test.

aberrations. For the CRT technique statistically significant differences were found for all aberrations after treatment. Statistically significant differences were also found for corneal Q for all diameters analysed. No significant differences were found between SL and CL regarding cHOA RMS ($p > 0.287$, t-test) or Q values for different diameters ($p > 0.164$, t-test). The changes in Q value depending on the diameter where the values are obtained are different depending on the procedure being considered (LASIK or CRT). Differences between Q_3 and Q_8 values were lower for refractive surgery procedures (0.5–0.6 for Q_3 to 0.3 for Q_8), than for CRT treatment group (1.15 for Q_3 to 0.45 for Q_8). CRT creates smaller treatment zones, more abrupt changes of curvature at the edge of the treatment zone (at the transition zone) and somewhat flattening outside the transition zone.

Correlations between corneal high order aberrations and asphericity

Table 3 shows the correlations and statistical significance for differences in aberrations and in Q for different diameters. As expected, the strongest correlations between the values of aberrations and Q were found in the values of spherical-like aberration, with a positive correlation between the alterations in Q (post-treatment minus pre-treatment) and those in spherical-like aberration (which becomes more positive after the intervention). These correlations are statistically significant for all diameters studied and for the three techniques and greatest for those diameters within the ablation zones (SL for 5 mm diameter, $r = 0.776$, $p < 0.001$; CL 6 mm diameter, $r = 0.853$, $p < 0.001$; CRT 5 mm diameter, $r = 0.627$, $p < 0.001$). Fig. 5 presents those correlations for spherical-like aberration, the one with the strongest correlation.

Discussion

The analysis of corneal Q for different diameters and its alterations as a consequence of surgical and non-surgical procedures for visual compensation allows us to obtain a more complete description of post-LASIK and post-CRT corneal contour, as well as to better differentiate how each of these strategies for myopia compensation works. The authors have recently shown that in normal corneas, Q becomes more negative as it is more peripherally analysed, especially for more astigmatic corneas.[10] However, the differences for normal corneas are small varying from −0.10 to −0.20 for corneas with astigmatism below 3 diopters and from −0.15 to −0.35 for those with astigmatism over 3 diopters. These values refer to Q calculations computed from 3 mm (Q_3) and 7 mm (Q_7) reference diameters. This demonstrates that even for the normal, non-treated cornea, a single value of corneal asphericity cannot suffice to accurately describe the corneal topography.

After the interventions evaluated in this study the cornea presents positive Q values, and these values become lower as the reference point for calculation moves towards periphery. In the case of refractive surgery, for an 8 mm diameter (Q_8), Q even becomes negative, whereas for ortokeratology it remains positive. However, it comes to attention that the differences are much larger for corneas that have undergone ortokeratology with alterations in the value of Q from 0.9 for Q_3 to 0.17 for Q_8. These results reveal another interesting phenomenon, which is the fact that post-treatment outcomes of Q vary considerably according to the corneal

Table 3 Correlation analysis and statistical significance between differences in cHOA (for three techniques) and differences in asphericity (post minus pre-intervention) for different corneal diameters.

Correlation/significance	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8
RMS_{3rd}						
SL	−0.443	−0.468	−0.464	−0.456	−0.428	−0.396
	0.020¥	0.014¥	0.015¥	0.017¥	0.026¥	0.041¥
CL	0.126	0.085	0.036	0.002	−0.066	−0.122
	0.530¥	0.673¥	0.858¥	0.992¥	0.745¥	0.546¥
CRT	−0.324	−0.335	−0.331	−0.322	−0.295	−0.262
	0.099*	0.087*	0.092*	0.102*	0.135*	0.187*
RMS_{4th}						
SL	−0.016	−0.051	−0.050	−0.068	−0.104	−0.103
	0.935¥	0.802¥	0.805¥	0.737¥	0.605¥	0.609¥
CL	0.433	0.404	0.362	0.342	0.284	0.249
	0.024¥	0.037¥	0.064¥	0.081¥	0.152¥	0.211¥
CRT	0.302	0.312	0.320	0.327	0.321	0.289
	0.126*	0.113*	0.103*	0.096*	0.103*	0.143*
RMS_{5th}						
SL	−0.448	−0.473	−0.467	−0.472	−0.448	−0.427
	0.019¥	0.013¥	0.014¥	0.013¥	0.019¥	0.026¥
CL	0.022	−0.028	−0.099	−0.126	−0.191	−0.245
	0.915¥	0.888¥	0.624¥	0.532¥	0.339¥	0.218¥
CRT	−0.222	−0.313	−0.340	−0.410	−0.404	−0.420
	0.265¥	0.112¥	0.083¥	0.033¥	0.037¥	0.029¥
RMS_{6th}						
SL	−0.272	−0.317	−0.318	−0.357	−0.396	−0.399
	0.170¥	0.107¥	0.107¥	0.068¥	0.041¥	0.039¥
CL	−0.218	−0.246	−0.273	−0.294	−0.315	−0.300
	0.275¥	0.215¥	0.167¥	0.137¥	0.109¥	0.129¥
CRT	−0.261	−0.285	−0.304	−0.332	−0.358	−0.388
	0.189*	0.149*	0.123*	0.090*	0.067*	0.045*
RMS_{Total}						
SL	−0.348	−0.378	−0.370	−0.374	−0.364	−0.337
	0.075¥	0.052¥	0.057¥	0.055¥	0.062¥	0.085¥
CL	0.125	0.084	0.030	0.000	−0.075	−0.120
	0.536¥	0.677¥	0.881¥	0.999¥	0.710¥	0.552¥
CRT	−0.045	−0.059	−0.060	−0.075	−0.082	−0.102
	0.825¥	0.770¥	0.766¥	0.712¥	0.683¥	0.613¥
$RMS_{Spherical\text{-}like}$						
SL	0.759	0.771	0.776	0.772	0.745	0.694
	0.000*	0.000*	0.000*	0.000*	0.000*	0.000*
CL	0.781	0.810	0.846	0.853	0.840	0.786
	0.000¥	0.000¥	0.000¥	0.000¥	0.000¥	0.000 ¥
CRT	0.594	0.622	0.627	0.623	0.585	0.505
	0.001*	0.001*	0.000*	0.001*	0.001*	0.007*
$RM_{Coma\text{-}like}$						
SL	−0.461	−0.480	−0.470	−0.461	−0.429	−0.365
	0.016*	0.011*	0.013*	0.015*	0.025*	0.061*
CL	−0.056	−0.084	−0.133	−0.171	−0.229	−0.267
	0.782¥	0.677¥	0.508¥	0.394¥	0.250¥	0.178¥
CRT	−0.199	−0.216	−0.212	−0.200	−0.172	−0.128
	0.320*	0.279*	0.288*	0.317*	0.391*	0.523*

Table 3 (*Continued*)

Correlation/significance	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8
RMS $RMS_{Astigmatism}$						
SL	−0.416	−0.447	−0.427	−0.435	−0.419	−0.415
	0.031¥	0.020¥	0.026¥	0.023¥	0.029¥	0.031¥
CL	−0.100	−0.142	−0.192	−0.220	−0.267	−0.283
	0.618¥	0.479¥	0.337¥	0.269¥	0.178¥	0.152¥
CRT	−0.025	−0.077	−0.086	−0.167	−0.158	−0.181
	0.901¥	0.704¥	0.668¥	0.405¥	0.431¥	0.367¥

SL, standard LASIK; CL, custom LASIK; CRT, corneal refractive therapy; RMS, root mean square higher order aberrations; *Q*, asphericity.
¥ Spearman correlation.
* Pearson correlation.

zone analysed for the different treatments. In clinical terms a given instrument (videokeratoscope) can apparently indicate a post-surgical prolate shape if takes the reference point more towards periphery and other could show an oblate shape if considering a more central reference point. This can also limit our ability to identify difference in the outcomes of different refractive treatments; for example, for a corneal topographer considering the peripheral zones at 4 mm (equivalent to the Q_8 in this study, differences in *Q* will be masked showing no statistical significantdifferences among treatments). Conversely, the differences are maximized as we go closer to the centre of the treatment zone (i.e. Q_3). Therefore, this multi-aspheric analysis of *Q* allows us to obtain more representative and ''unbiased'' information about post-treatment corneal *Q*-value irrespective of the instrument used to obtain the measurements. In a certain way it will act as a normalization procedure.

As far as current knowledge is concerned, no studies are known that simultaneously analyse the effects caused by standard LASIK surgery, by customized LASIK surgery and

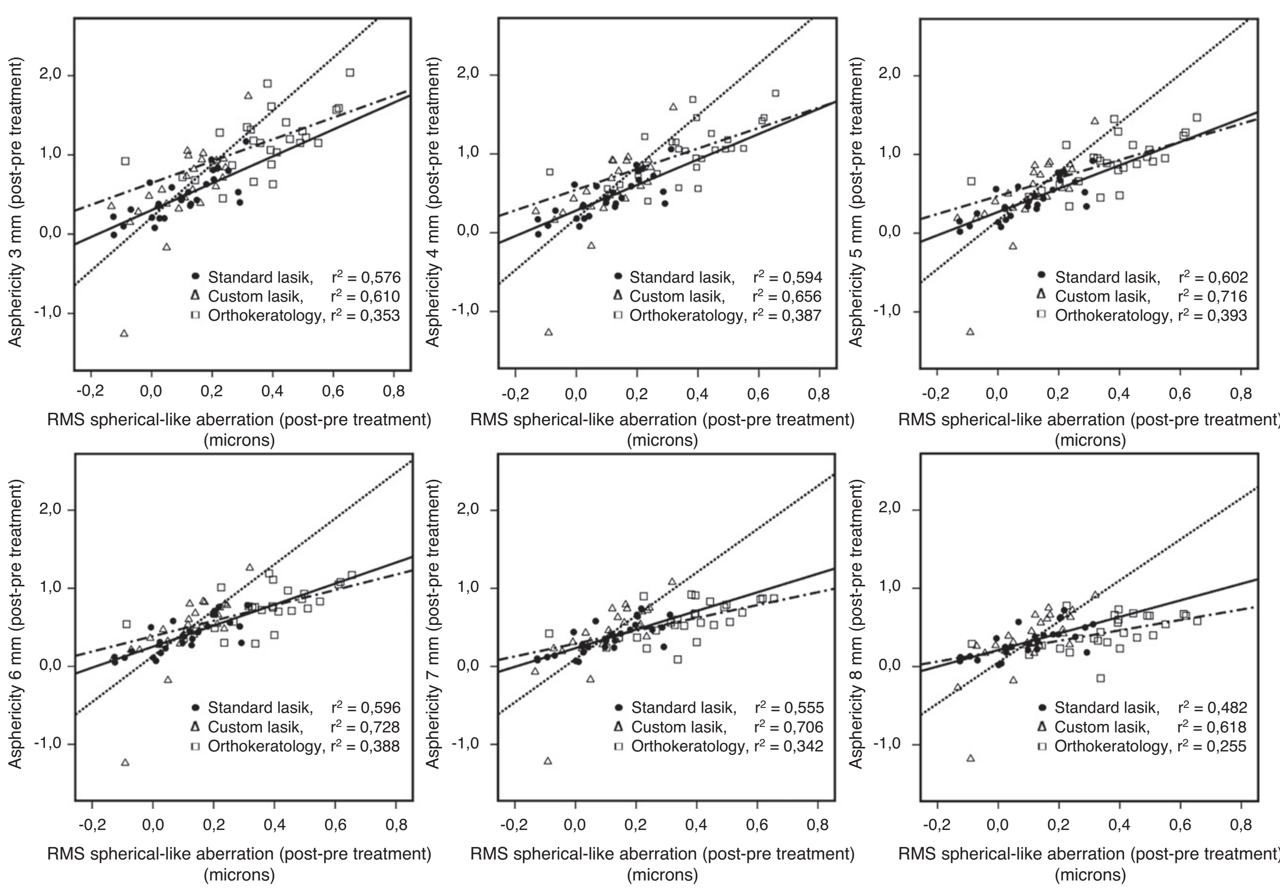

Figure 5 Correlation between differences in HOA (spherical-like aberration for a 6-mm pupil) and differences in asphericity for different corneal diameters. Filled circles for SL (full line), open triangle for CL (hatched line) and open squares for CRT (line point and trace).

by orthokeratology on cHOA and corneal asphericity (Q). The results of the present work allow us to characterize the changes in cHOA and asphericity confirming that different treatments have a significantly different impact on these descriptors of corneal shape and optical properties. One of the purposes of this study was the analysis of the optical quality of the corneal front surface among these three techniques, an effort was made to ensure that baseline values of refractive error were comparable for the different groups, since several studies have reported increases of high order aberrations according to the amount of refractive error.[13,26,27]

As seen on the results (Fig. 1), in the post-treatment we found higher increase of high order aberrations in CRT compared to LASIK surgery. Corneal Q also changed for all three techniques from the initially prolate shape to positive values (oblate shape). The alterations in corneal Q after the treatments represent an important impact on HOA and especially on spherical-like aberrations and, therefore, on the optical function of the eye[14,28,29] and its visual experience as spherical aberration is one of the most relevant optical errors influencing on the degradation of the image quality.[30,31]

Similar results were found by Anera et al., who analyzed mean values of corneal Q for 24 eyes submitted to LASIK surgery. In their study they found an initial Q of -0.12 changing to a mean value of +0.41 3 months after surgery.[6] The study recently published by Anera et al., in which they analyse the differences between LASIK and CRT with pupil values of 5 mm, for values of refractive error, age and number of eyes similar to ours, they have found increases in third, fourth and fifth order aberrations, for both emmetropization processes, with these increases being higher for CRT. In the same study the Q values found were higher after CRT ($+0.45 \pm 0.42$) than after LASIK ($+0.13 \pm 0.12$). This is in agreement with the results of the present study, although those authors have not performed the analysis for different Q zones.[14]

Our results show that spherical-like aberrations are those which suffer the highest increase after the treatments (fourth order and spherical-like aberrations). This is not surprising considering the limitations in pre-treatment astigmatism, thus reducing the potential increase in secondary astigmatism and other aberrations, and the requirement of well centred treatments thus reducing the amount of coma-like aberration. However, the values of coma-like aberrations were higher for CRT cases, which agrees with the fact that for this therapy there is a certain degree of decentring compared with LASIK being responsible for such aberration.[22] An alternative explanation for this difference could be found on potentially different reference points for both treatments. However, in our study, both LASIK and CRT treatments were intended to be centred on pupillary area and VolCT analysed the HOA with reference to pupil centre as well, thus equalizing this potential source of error among treatments. Both spherical-like and coma-like aberrations are those which produce a larger deterioration in the optical quality of the eye, whereas aberrations of a higher order (5th, 6th and above) exert a lesser influence on vision.[30,31] The increase in spherical-like aberrations and the changes in Q are related by the different topographical profiles created after each intervention (smaller optical zone and higher corneal steepening at the edge of the optical zone for CRT compared to LASIK procedures).[4] From our analysis, the higher correlations between spherical-like aberration and Q values obtained for different diameters were found for Q_5, Q_6 and Q_7. This might be expected considering that the spherical-like aberration has been obtained for a 6 mm diameter zone.

One of the limitations of this study was to have obtained corneal aberrations only before and after the treatments, and not having measured total optical aberrations of the eye. As is commonly known, total aberrations are the result of the combination of corneal and internal aberrations.[32,33] However, it is to be expected that the alterations observed in total aberrations of the eye follow the same pattern than those observed on the ACS, where the largest aberrations occur, and such was demonstrated by Anera et al.'s[14] recent study both for refractive LASIK surgery and CRT. In this study Q values obtained in each corneal location were averaged among individuals. As stated by de Ortueta and Arba-Mosquera, using simple arithmetic's to average asphericity of different individuals might present some limitations. The authors propose a mathematical methodology to compute Q values in order to provide a more consistent result of the average asphericity from different individual corneas.[34] Moreover, both Q values and cHOA are obtained from the same data, thus must reflect similar changes as the present study shows. However, we still believe that there is a rationale to explore both of them. Q values show the mathematical representation of shape changes and are used in clinical practice quite frequently. Thus, it is important to highlight how they can vary depending on the area being analysed, particularly after reshaping procedures. This fact is even more critical after orthokeratology given the larger changes between Q_3 and Q_8. At the same time, cHOA provide an insight on the optical quality of the surface and provide information about the visual quality after these procedures. Another limitation of the present study is the potential decentration between the treated areas which are targeted regarding the pupil centre and the aberration analysis carried out with reference to the corneal centre as analysed by the corneal topographer. As reported by other authors, this differences can have an impact on comatic aberrations.[35]

The new concept of multi-asphericity for the ACS has been applied in defining the normal cornea by the authors[10] and has now been applied to the modified corneas by means of different refractive procedures, surgical and non-surgical. Its results have different implications; a unique value of asphericity might confound the results of different refractive treatments whereas a more complex determination of asphericity at different diameters can elucidate significant differences in the behaviour of those treatments, and other field of application could be the definition of the functional optical zone of the cornea previously defined by others as the zone where the corneal curvature will vary only within a narrow interval of power.[36] Finally, the multi-aspheric modelisation of the human cornea (before and after refractive interventions) will help to design optical devices that mimic the natural aspheric nature of the cornea for example with the purpose of fitting contact lenses or to develop optical devices that compensate or reinforce a certain desirable refractive pattern for the whole eye from the asphericity pattern of the ACS.

The present results show that there is deterioration in terms of multi-aspheric description of the ACS compared to the pre-treatment situation. Although the present study does not report data on the total wavefront aberration, it is expected that those changes reported here will be closely related to a degradation of the optical quality of the eye.[14] That same deterioration found by Anera et al.[14] was larger for the CRT group than for LASIK surgery which agrees with our results; in addition we have shown absence of significant differences between standard LASIK surgery and customized LASIK surgery regarding multi-aspheric corneal shape description after the interventions and the inherent aberrations generated.

In summary, literature reports values of corneal asphericity in normal populations that range from −0.01 to −0.80.[37–40] Indeed, as shown here, both in normal but above all, in corneas altered by refractive procedures, the same instrument might report values of asphericity completely different.

Conflicts of interest

The authors have no conflicts of interest to declare.

Acknowledgments

This work was supported by a grant from the Science and Technology Foundation (FCT) of Ministry of Science and Superior Education (MCES) (European Social Funding) under contract BD/61768/2009 granted to Dr. António Queirós. The authors have no proprietary interest in any of the instruments or materials mentioned in this article.

References

1. Moreno-Barriuso E, Lloves JM, Marcos S, Navarro R, Llorente L, Barbero S. Ocular aberrations before and after myopic corneal refractive surgery: LASIK-induced changes measured with laser ray tracing. *Invest Ophthalmol Vis Sci*. 2001;42:1396–1403.
2. Sorbara L, Fonn D, Simpson T, Lu F, Kort R. Reduction of myopia from corneal refractive therapy. *Optom Vis Sci*. 2005;82:512–518.
3. Villa-Collar C, Gutierrez R, Jimenez JR, Gonzalez-Meijome JM. Night vision disturbances after successful LASIK surgery. *Br J Ophthalmol*. 2007;91:1031–1037.
4. Queirós A, Gonzalez-Meijome JM, Villa-Collar C, Gutierrez AR, Jorge J. Local steepening in peripheral corneal curvature after corneal refractive therapy and LASIK. *Optom Vis Sci*. 2010;87:432–439.
5. Holladay JT, Janes JA. Topographic changes in corneal asphericity and effective optical zone after laser in situ keratomileusis. *J Cataract Refract Surg*. 2002;28:942–947.
6. Anera RG, Jimenez JR, Jimenez dB, Bermudez J, Hita E. Changes in corneal asphericity after laser in situ keratomileusis. *J Cataract Refract Surg*. 2003;29:762–768.
7. Gonzalez-Meijome JM, Sanudo-Buitrago F, Lopez-Alemany A, Almeida JB, Parafita MA. Correlations between central and peripheral changes in anterior corneal topography after myopic LASIK and their implications in postsurgical contact lens fitting. *Eye Contact Lens*. 2006;32:197–202.
8. Sridharan R, Swarbrick H. Corneal response to short-term orthokeratology lens wear. *Optom Vis Sci*. 2003;80:200–206.
9. Gonzalez-Meijome JM, Jorge J, Queiros A, Almeida JB, Parafita MA. A comparison of the ARK-700A autokeratometer and Medmont E300 corneal topographer when measuring peripheral corneal curvature. *Ophthalmic Physiol Opt*. 2004;24: 391–398.
10. Gonzalez-Meijome JM, Villa-Collar C, Montes-Mico R, Gomes A. Asphericity of the anterior human cornea with different corneal diameters. *J Cataract Refract Surg*. 2007;33: 465–473.
11. Du CX, Shen Y, Wang Y. Comparison of high order aberration after conventional and customized ablation in myopic LASIK in different eyes of the same patient. *J Zhejiang Univ Sci B*. 2007;8:177–180.
12. Montes-Mico R, Rodriguez-Galietero A, Alio JL, Cervino A. Contrast sensitivity after LASIK flap creation with a femtosecond laser and a mechanical microkeratome. *J Refract Surg*. 2007;23:188–192.
13. Hiraoka T, Matsumoto Y, Okamoto F, et al. Corneal higher-order aberrations induced by overnight orthokeratology. *Am J Ophthalmol*. 2005;139:429–436.
14. Anera RG, Villa-Collar C, Jimenez JR, Gutierrez R. Effect of LASIK and contact lens corneal refractive therapy on higher order aberrations and contrast sensitivity function. *J Refract Surg*. 2009;25:277–284.
15. Oshika T, Klyce SD, Applegate RA, Howland HC, El Danasoury MA. Comparison of corneal wavefront aberrations after photorefractive keratectomy and laser in situ keratomileusis. *Am J Ophthalmol*. 1999;127:1–7.
16. Queiros A, Villa-Collar C, Gonzalez-Meijome JM, Jorge J, Gutierrez AR. Effect of pupil size on corneal aberrations before and after standard laser in situ keratomileusis, custom laser in situ keratomileusis, and corneal refractive therapy. *Am J Ophthalmol*. 2010;150:97–109.
17. Applegate RA, Hilmantel G, Howland HC, Tu EY, Starck T, Zayac EJ. Corneal first surface optical aberrations and visual performance. *J Refract Surg*. 2000;16:507–514.
18. Lu F, Simpson T, Sorbara L, Fonn D. Malleability of the ocular surface in response to mechanical stress induced by orthokeratology contact lenses. *Cornea*. 2008;27:133–141.
19. Calossi A. Corneal asphericity and spherical aberration. *J Refract Surg*. 2007;23:505–514.
20. Patel S, Marshall J, Fitzke FW, Gartry DS. The shape of the corneal apical zone after excimer photorefractive keratectomy. *Acta Ophthalmol (Copenh)*. 1994;72:588–596.
21. Holladay JT, Dudeja DR, Chang J. Functional vision and corneal changes after laser in situ keratomileusis determined by contrast sensitivity, glare testing, and corneal topography. *J Cataract Refract Surg*. 1999;25:663–669.
22. Lu F, Simpson T, Sorbara L, Fonn D. The relationship between the treatment zone diameter and visual, optical and subjective performance in Corneal Refractive Therapy lens wearers. *Ophthalmic Physiol Opt*. 2007;27:568–578.
23. Harper CL, Boulton ME, Bennett D, et al. Diurnal variations in human corneal thickness. *Br J Ophthalmol*. 1996;80:1068–1072.
24. Handa T, Mukuno K, Niida T, Uozato H, Tanaka S, Shimizu K. Diurnal variation of human corneal curvature in young adults. *J Refract Surg*. 2002;18:58–62.
25. Gonzalez-Meijome JM, Villa-Collar C. Nomogram, corneal topography, and final prescription relations for Corneal Refractive Therapy. *Optom Vis Sci*. 2007;84:59–64.
26. Oshika T, Miyata K, Tokunaga T, et al. Higher order wavefront aberrations of cornea and magnitude of refractive correction in laser in situ keratomileusis. *Ophthalmology*. 2002;109:1154–1158.
27. Rosa N, De Bernardo M, Lanza M, Borrelli M, Fusco F, Flagiello A. Corneal aberrations before and after photorefractive keratectomy. *J Optom*. 2008;1:53–58.

28. Hiraoka T, Okamoto C, Ishii Y, Kakita T, Oshika T. Contrast sensitivity function and ocular higher-order aberrations following overnight orthokeratology. *Invest Ophthalmol Vis Sci*. 2007;48:550–556.
29. Oshika T, Tokunaga T, Samejima T, Miyata K, Kawana K, Kaji Y. Influence of pupil diameter on the relation between ocular higher-order aberration and contrast sensitivity after laser in situ keratomileusis. *Invest Ophthalmol Vis Sci*. 2006;47:1334–1338.
30. Applegate RA, Sarver EJ, Khemsara V. Are all aberrations equal? *J Refract Surg*. 2002;18:S556–S562.
31. Ferrer-Blasco T, Montés-Micó R, Charman WN, Cerviño Exposito A, Gonzalez-Meijome J. Positive and negative effect of optical aberrations on retinal image quality. *Atti della ''Fondazione Giorgio Ronchi''*. 2009;64: 307–311.
32. Artal P, Guirao A, Berrio E, Williams DR. Compensation of corneal aberrations by the internal optics in the human eye. *J Vis*. 2001;1:1–8.
33. Marcos S, Barbero S, Llorente L, Merayo-Lloves J. Optical response to LASIK surgery for myopia from total and corneal aberration measurements. *Invest Ophthalmol Vis Sci*. 2001;42:3349–3356.
34. De Ortueta D, Arba MS. Mathematical properties of asphericity: a method to calculate with asphericities. *J Refract Surg*. 2008;24:119–121.
35. Lu F, Wu J, Qu J, et al. Association between offset of the pupil center from the corneal vertex and wavefront aberration. *J Optom*. 2008;1:8–13.
36. Tabernero J, Klyce SD, Sarver EJ, Artal P. Functional optical zone of the cornea. *Invest Ophthalmol Vis Sci*. 2007;48:1053–1060.
37. Holmes-Higgin DK, Baker PC, Burris TE, Silvestrini TA. Characterization of the aspheric corneal surface with intrastromal corneal ring segments. *J Refract Surg*. 1999;15:520–528.
38. Mandell RB. The enigma of corneal contour. *CLAO J*. 1992;18:173–267.
39. Townsley MG. New knowledge of the corneal contour. *Contacto*. 1970;14:38–43.
40. Eghbali F, Yeung KK, Maloney RK. Topographic determination of corneal asphericity and its lack of effect on the refractive outcome of radial keratotomy. *Am J Ophthalmol*. 1995;119:275–280.