

Wavefront Aberrations Prior to and post-intrastromal Corneal Ring Segment Implantation in Keratoconus

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PURPOSE: To describe the wavefront changes induced by the implantation of Ferrara intrastromal corneal ring segments (ICRS) in keratoconus.

METHODS: ICRS were implanted in 96 eyes of 92 patients with keratoconus grade I, II and III. Ocular aberrations were examined using the Nidek OPD scan wavefront aberrometer.

RESULTS: There was an improvement in uncorrected distance visual acuity (UDVA) and corrected distance visual acuity (CDVA) for all grades of keratoconus. For grade I the mean UDVA improved from 0.94 ± 0.38 to 0.65 ± 0.38 LogMAR ($p < 0.001$) and CDVA from 0.35 ± 0.17 to 0.19 ± 0.16 ($p < 0.001$). In keratoconus grade II the mean UDVA improved from 1.15 ± 0.35 to 0.67 ± 0.36 LogMAR ($p < 0.001$) and CDVA from 0.50 ± 0.22 to 0.25 ± 0.18 ($p < 0.001$). In grade III the mean UDVA improved from 1.28 ± 0.28 to 0.92 ± 0.45 LogMAR ($p < 0.001$) and CDVA from 0.65 ± 0.27 to 0.46 ± 0.25 ($p < 0.001$). RMS at 3mm improved ($p < 0.01$) in grades I and II but not in grade III ($p = 0.75$) while RMS at 5mm improved in all groups. However, this was only statistically significant in grade I ($p < 0.001$). Primary Coma statistically decreased in patients with grade I and II ($p < 0.01$) but not in grade III ($p = 0.10$). Negative spherical aberration increased in all groups. All other peripheral aberrations statistically increased, except for trefoil in grade I that decreased but this had no statistical significance ($p = 0.73$).

CONCLUSION: Ferrara ICRS improved CDVA and UDVA in all groups, decreasing total aberrations, coma and tilt, while increasing other HOAs.

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INTRODUCTION

Measurement of the eye wavefront has been used for various reasons, especially in customized corneal ablation^{1,2} where it was made popular. It is also very useful in clinical practice to evaluate the optical quality of the eye and irregular astigmatism³ by detecting higher-order aberrations (HOA). Studies have shown that coma and spherical aberration can affect the high-resolution imaging of any optical system, including the eye.^{4,5,6}

Anterior corneal aberration analysis has been demonstrated to be an effective tool for detecting and grading keratoconus^{7,8,9}. This is because in keratoconus there can be a substantial increase in higher-order aberrations, resulting in visual acuity loss that cannot be corrected with conventional spectacles or soft contact lenses.

Several studies have compared keratoconic eyes and their relationship with corneal aberrations. It has been shown that there are increased HOAs, particularly in coma and spherical aberration^{9,10,11}. The mean wavefront error can be quantitatively expressed as the root mean square (RMS). Third order and higher are considered higher-order aberrations (HOA).

Ferrara intrastromal corneal ring segments (ICRS) have been used effectively to treat keratoconus and related keratectasias.^{12,13,14,15} A recently published study¹⁶ has shown that the Ferrara ICRS, in addition to improving uncorrected and corrected visual acuity, can also improve corneal asphericity, reducing the hyperprolate state usually found in keratoconus. This finding, along with wavefront analysis, is important as a tool for evaluation of quality of vision after ICRS implantation.

The purpose of this study was to evaluate the wavefront corneal changes induced by the implantation of the Ferrara ICRS, and its relationship to visu-

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al acuity in keratoconus grade I, II and III using the Amsler-Krumeich scale.

MATERIALS AND METHODS

In this study we retrospectively reviewed patient records involving the 96 eyes of 92 patients with keratoconus, grade I, II and III detected using the Amsler-Krumeich scale. These patients consecutively underwent surgery performed by the same experienced surgeon (RS) using the manual technique. The rings were chosen according to the Ferrara Ring Nomogram,¹⁵ and only non-complicated surgeries were included in these study.

Fifty-nine patients were male (61,4%) and 37 were female (38,6%). The mean age of patients was 29.04 ± 7.43 years old (range: 17 to 47 years-old). The mean follow-up time was 13.6 ± 11.2 [SD] months (range 3 to 60 months). After a complete ophthalmic examination and a thorough discussion of the risks and benefits of the surgery, the patients gave written informed consent. The main indication for ICRS implantation was contact lens intolerance and/or progression of ectasia. Disease progression was defined by: worsening of uncorrected distance visual acuity (UDVA) and corrected distance visual acuity (CDVA), progressive intolerance to contact lens wear and progressive corneal steepening documented by the topography.

Total (corneal and internal) wavefront analysis was performed with the Nidek OPD-Scan II (Optical Path Difference Scanning System; NIDEK Co Ltd, Gamagori, Japan). This machine provides total aberrometric analysis by deconstructing the whole eye into anterior corneal surface, posterior corneal surface, anterior chamber, lens, vitreous and retina. It uses the same principle as dynamic retinoscopy by calculating the time and intensity it takes reflected light from the retina to reach 1440 given points over a 6 mm pupil, comparing to the theoretical time it would take light to illuminate the point in an eye with perfect emmetropia.¹⁷ Previous studies confirmed the precision and repeatability of its results.¹⁸

Statistical analysis included preoperative and postoperative UDVA, CDVA, total aberration, Total Root Mean Square (RMS) at 3 mm (RMS3) and 5 mm (RMS5), Spherical aberration, primary coma, Trefoil, Tetra foil,

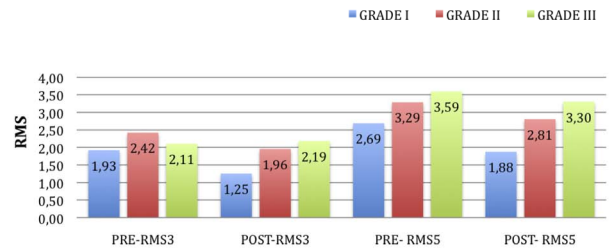


Figure 1. Preoperative and postoperative RMS 3 and 5.

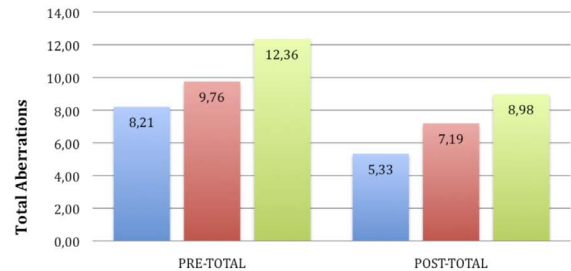


Figure 2. Preoperative and postoperative total aberrations.

induced astigmatism (named as high astigmatism by the aberrometer) and Tilt. Statistical analysis was carried out using Excel (2010, Microsoft Corp.). Student’s t test for paired data were used to compare preoperative and postoperative data, and Pearson Test for Correlation between the data.

RESULTS

After analyzing the data on keratoconus grade I, II and III using the Amsler-Krumeich scale, the results were as follows (Table 1, Figures 1,2,3 and 4):

Keratoconus grade I: The mean UDVA improved from 0.94 ± 0.38 to 0.66 ± 0.38 LogMAR (p < 0.001) and the mean CDVA improved from 0.35 ± 0.17 to 0.19 ± 0.16 LogMAR (p < 0.001). The RMS3 values decreased from 1.92 ± 0.73 to 1.25 ± 0.58 (p < 0.001); the RMS5 decreased from 2.69 ± 1.10 to 1.88 ± 0.81 D (p < 0.001); Total aberrations decreased from 8.21 ± 3.14 to 5.33 ± 2.31 microns (p < 0.001); coma decreased

	PreopUDVA	PostopUDVA	p	PreopCDVA	PostopCDVA	p
Grade I	0.94 ±0.38	0.66 ±0.38	< 0,001	0.35 ±0.18	0.19 ±0.16	< 0,001
Grade II	1.15 ±0.35	0.68 ±0.36	< 0,001	0.50 ±0.22	0.25 ±0.18	< 0,001
Grade III	1.28 ±0.25	0.93 ±0.35	< 0,001	0.65 ±0.27	0.46 ±0.25	< 0,001

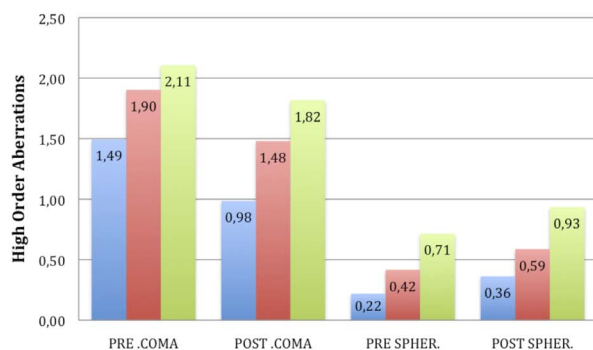


Figure 3. Preoperative and postoperative central HOAs.

from 1.49 ± 0.73 to 0.98 ± 0.50 microns ($p = 0.002$); tilt decreased from 4.64 ± 1.88 to 2.33 ± 1.12 microns ($p < 0.001$); trefoil decreased from 1.05 ± 0.49 to 1.00 ± 0.49 microns ($p = 0.73$); tetrafoil increased from 0.16 ± 0.11 to 0.54 ± 0.21 microns ($p < 0.001$); spherical aberration increased from 0.21 ± 0.16 to 0.36 ± 0.25 microns ($p = 0.01$).

Keratoconus grade II: the mean UDVA improved from 1.15 ± 0.35 to 0.67 ± 0.36 LogMAR ($p < 0.001$) and the mean CDVA improved from 0.50 ± 0.22 to 0.25 ± 0.18 LogMAR ($p < 0.001$). The RMS3 values decreased from 2.42 ± 1.12 to 1.96 ± 0.88 ($p = 0.002$); RMS5 decreased from 3.29 ± 1.22 to 2.81 ± 1.47 ($p = 0.08$); total aberrations decreased from 9.76 ± 3.55 to 7.19 ± 2.56 microns ($p < 0.001$); coma decreased from 1.90 ± 0.72 to 1.48 ± 0.82 microns ($p = 0.008$); tilt decreased from 5.42 ± 2.54 to 3.60 ± 1.97 microns ($p < 0.001$); trefoil increased from 1.14 ± 0.54 to 1.42 ± 0.63 microns ($p = 0.02$); tetrafoil increased from 0.17 ± 0.09 to 0.60 ± 0.22 microns ($p < 0.001$); spherical aberration increased from 0.42 ± 0.24 to 0.59 ± 0.30 microns ($p = 0.001$).

Keratoconus grade III: the mean UDVA improved from 1.28 ± 0.28 to 0.92 ± 0.45 LogMAR ($p < 0.001$) and the mean CDVA improved from 0.65 ± 0.27 to 0.46 ± 0.25 LogMAR ($p < 0.001$). The RMS3 values increased from 2.11 ± 1.02 to 2.19 ± 1.20 ($p = 0.75$); RMS5 decreased from 3.60 ± 1.53 to 3.30 ± 1.82 ($p = 0.39$); total aberrations decreased from 12.36 ± 3.41 to 8.98 ± 3.31 microns ($p < 0.001$); coma decreased from 2.11 ± 0.92 to 1.82 ± 1.15 microns ($p = 0.10$); tilt decreased from 5.37 ± 2.36 to 3.79 ± 2.26 microns ($p = 0.001$); trefoil increased from 0.98 ± 0.49 to 1.41 ± 0.75 microns ($p = 0.01$); tetrafoil increased from 0.17 ± 0.11 to 0.62 ± 0.39 microns ($p < 0.001$); spherical aberration increased from 0.71 ± 0.36 to 0.93 ± 0.50 microns ($p = 0.01$).

DISCUSSION

The decrease of vision in patients with keratoconus is not only caused by sphero-cylindrical refractive errors (low order aberrations) due to elevated corneal curvature,

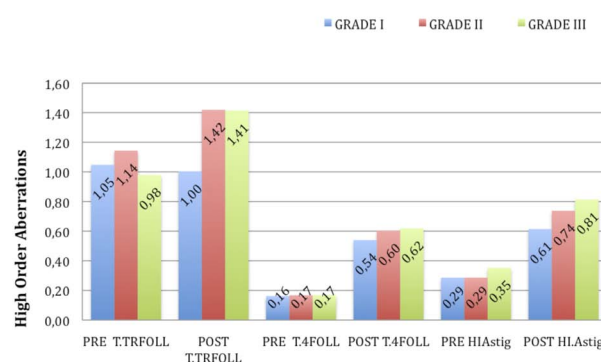


Figure 4. Preoperative and postoperative peripheral HOAs.

but also to a significant extent by high order ones. This is clearly explained by the fact that spectacles in most cases are not able to provide full correction. The predominant defect is the coma aberration, specifically its vertical component^{19,20,21,22,23}. This was so evident that different studies using different instruments had the same result^{19,20,21,22,23}. Alió and Shabayek²⁴ used this property to modify the classic Amsler-Krumeich classification for keratoconus, the amount of coma aberration being one of the parameters.

In addition, trefoil, tetrafoil and secondary astigmatism are greater in keratoconic eyes^{19,20,21,22,23}. When the directions of each term were analyzed by Zernike vector analysis, keratoconic eyes tend to have a reverse coma pattern, that is, a prominent vertical coma with an inferior slow pattern.²⁰ In addition, trefoil aberration was the opposite of that of normal eyes.²⁰

The relationship between HOAs and visual function is complicated and not fully understood. Applegate et al¹⁹ demonstrated that all aberrations are not equivalent, in that different Zernicke polynomial coefficients with the same amount of RMS error result in varying degrees of degradation in high and low contrast acuity. In normal subjects, the RMS wavefront error appears to have a low correlation to visual acuity, in the absence of irregular corneas.

Maeda et al²⁰ evaluated eyes with mild and moderate keratoconus using a KR-9000 aberrometer (Topcon, Tokyo, Japan). The study was one of the first to look at a population of keratoconus and to identify dominant higher-order aberrations. In a study published by Jafri et al⁹ in 2007 higher vertical coma and higher RMS values were found in patients with suspected and early keratoconus. Similar results were found by Pantanelli et al.²¹ when studying the wavefront in keratoconus. Mean RMS values of 2.24 ± 1.22 D were found, which are similar to the values in the present study. These values are approximately 5.5 times the 0.41 ± 0.16 D found in normal corneas.

Pinero et al.²⁵, in a study comparing two different types of ICRS (Intacs and Keraring), found that coma-like aberrations tended to decrease after ICRS

implantation, and the change occurred more rapidly with the Keraring. They also compared the visual and wavefront outcomes between the manual and the femtosecond laser, and found that both procedures provide similar visual and refractive outcomes.

More limited aberrometric correction was observed in the manual technique. They found that the use of mechanical tunnelization specifically for Intacs implantation in eyes with early to moderate keratoconus has limited the potential aberrometric correction of these implants because the procedure itself generated new aberrations, especially negative primary spherical aberration and primary coma. This trend was not specifically confirmed for Kerarings segments because of the limitations of the study in the sample size for this segment type.

Analyzing the pre and post-operative by Amsler-Krumeich keratoconus scale, in grade I, II and III groups, the Ferrara intrastromal corneal rings statistically improved UDVA and CDVA (TABLE 1), providing similar results as showed by a recently published large sample study²⁶.

We showed that the postoperative RMS value is improved in mild cases of keratoconus. RMS at 3mm significantly improved ($p < 0.01$) in grade I and II but not in grade III ($p = 0.75$) which slightly increased. RMS at 5mm improved in all groups, but was only statistically significant in grade I ($p < 0.001$) but not in grade II ($p=0.08$) and III ($p=0.38$) (Figure 1). Corneal flattening reduces central keratometry in keratoconus²⁶ reducing the amount of myopia. This can be indirectly evaluated by total corneal aberration that statistically decreased in all groups. ($p < 0.01$) (Figure 2)

In the present study we found a statistically significant decrease in coma in patients in groups I and II ($p < 0.01$) but not in grade III ($p=0.10$). As for the spherical aberration the values statistically increased in all groups, in accordance with results also found in another studies^{27,28}. All other peripheral aberrations statistically increased, except for trefoil in cone I that decreased but had no statistical significance ($p=0.73$).

The overall improvement in UDVA and CDVA can be related to a decrease in Total aberrations, by the reduction in the myopic component (corneal flattening) and HOAs, especially Coma and Tilt, which are related to the central area of the cornea and therefore have an important role in the quality of vision. The increase in trefoil, tetrafoil and secondary astigmatism can be explained by the increase of peripheral aberration measured in the 6mm area, which includes the area where the ICRS is implanted, but their influence on the visual outcome is less significant than central ones. Spherical aberrations, despite the decrease in the prolateness of the cornea, showed statistically significant increases. This was also found in a study by Pinero et al.²⁵

Our study showed that there was improvement in the quality and quantity of vision in all keratoconus groups. The best clinical outcomes were found in patients with keratoconus grade I and II.

Further studies with larger samples and longer follow-up periods must be undertaken in order to confirm the presented results..

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