# Optical and Topographic Changes in Keratoconus After Implantation of Ferrara Intracorneal Ring Segments

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## ABSTRACT

**PURPOSE:** To assess the morphological, optical, and visual properties of the cornea before and after implantation of Ferrara intracorneal ring segments (ICRS) and compare them to normal values.

**METHODS:** Thirty-seven keratoconic eyes were implanted with Ferrara ICRS and compared pre- and postoperatively with 38 non-keratoconic (normal) eyes. Examinations were performed using the NIDEK Optical Path Difference (OPD)-Scan II and analyzed using OPD-Station software. Keratometric data were assessed, in addition to OPD, Zernike coefficients, point spread function (PSF), and modulation transfer function (MTF).

**RESULTS:** Considering correlations, the central 3 mm cornea was found responsible for the low quality vision in keratoconus ($P<.01$). After implantation of Ferrara ICRS, all keratometric parameters improved significantly. Optical path difference also improved. Except for tilt and other lower order Zernike coefficients, higher order aberrations, PSF, and MTF did not change. The effect of flattening is greater at the central 3 mm, but the paracentral changes are responsible for the residual defects (ie, incomplete improvements of high optical and visual functions).

**CONCLUSIONS:** Ferrara ICRS improve topographic and visual results in keratoconic eyes. [*J Refract Surg*. 2010;26(11):871-880.]


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Ferrara intracorneal ring segments (ICRS; Ferrara Ophthalmics, Belo Horizonte, Brazil) provide improvement in both visual and topographic parameters when properly implanted in eyes with keratoconus.[1-3] Studies focusing on the procedure mostly concentrated on lower order aberrations such as defocus and astigmatism. Topography, when assessed, was not largely analyzed.[1-3]

Ferrara ICRS act by flattening the central part of the cornea, using the general principle for corneal implants: adding corneal tissue to the periphery[4] and lifting the tips of the segment, leading to additional flattening by the body of the segment at the meridian opposite the site of insertion.[1]

A Ferrara ICRS differs from Intacs (another implant with different criteria; Addition Technology Inc, Des Plaines, Illinois) in that it has a smaller radius of curvature (1.5 mm compared to 3.5 mm) and a triangular anterior surface instead of a flat one.[1] The unique triangular shape with a flat posterior surface is supposed to induce a prismatic effect that reduces glare.[2] However, night visual symptoms are still common for all designs.

The NIDEK OPD-Scan II (Optical Path Difference; NIDEK Co Ltd, Gamagori, Japan) is a multipurpose instrument that combines Placido-based corneal topography with wavefront aberrometry of the entire eye.[5] It is based on an automatic retinoscopy principle, allowing high quality analysis of approximately 1440 points over a 6-mm pupil.[6] Previous studies confirmed the precision and repeatability of its results.[7] A detailed topographic and aberrometric analysis is yielded for the examined eye, especially with the processing of the data via OPD-Station software (NIDEK Co Ltd).[5]

In this study, the OPD-Scan II and OPD-Station software were used to assess the criteria of keratoconic eyes in com-

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TABLE 1

**Nomogram for Choosing Ferrara Intracorneal Ring Segments**

| | Centration of the Cone | | | |
|---|---|---|---|---|
| **Simulated Keratometry** | **Type I** | **Type II** | **Type III** | **Type IV** |
| K1 & K2 <50.00 D | 0/150 | 0/150 | 150/150 | 150/150 |
| K1 >50.00 D & K2 <50.00 D | 0/200 | 0/200 | 150/200 | 200/200 |
| K1 & K2 >50.00 D | 150/250 | 150/250 | 200/250 | 250/250 |

*Note. Numbers represent the thickness of segments in microns.*

parison to normal eyes. The effect of Ferrara ICRS implantation was also analyzed.

## PATIENTS AND METHODS

This was a prospective, controlled, comparative study, in which 37 eyes of 26 patients reporting decreased vision and having a topographic diagnosis of keratoconus were enrolled. The control group comprised 38 eyes of 19 patients who had normal corneas that were eligible for LASIK. All patients signed a written consent in accordance to the tenets of the Declaration of Helsinki. No institutional review board approval was required for this study.

### PATIENT SELECTION

Preoperatively, patients were excluded if they had pathology in addition to keratoconus. Postoperatively, patients were excluded if any adverse events occurred during the procedure or follow-up. Only patients with good centration and depth implantation were included. Accordingly, two patients were excluded from the study due to a presumed sterile postoperative inflammation (which resolved with topical corticosteroids), and one patient was excluded due to improper centration. These three patients were not further analyzed. The control group was considered to have no ocular findings other than the refractive error to be corrected.

The number and thickness of Ferrara ICRS were chosen according to the surgeon's personal nomogram (Table 1). This nomogram was developed using the simulated keratometry (sim K) values in relation to the type of cone centration. Keratometric values were used rather than refraction. Type of cone centration depends on the distribution of cone position on the axial topography map in respect to the steep meridian.

- Type I: 100% of the cone lies below the steep meridian (peripheral cone).
- Type II: 25% of the cone lies above and 75% lies below the steep meridian.
- Type III: 33.5% of the cone lies above and 66.5% lies below the steep meridian.
- Type IV: 50% of the cone lies above and 50% lies below the steep meridian (central cone).

### SURGERY AND EVALUATION

Segments were implanted using the manual dissection technique.[1,2]

All eyes were examined with the OPD-Scan II before and at least 1 month after Ferrara ICRS implantation. Data were exported to the OPD-Station software and analyzed. For all eyes, age, gender, and left right eye were noted. The interval between surgery and postoperative examination was also noted, in addition to the type of cone and the segments used.

### ANALYSIS OF CORNEAL SURFACE

Simulated K values were extracted from the axial map as the steep meridian (sim K1) and flat meridian (sim K2). The difference between both is the topographic cylinder value (sim Kcyl). The average keratometric reading was presented as avg K (extracted from topo-classifier included in the OPD-Station).

The central 3-mm K-readings of the cornea were extracted from the instantaneous map to evaluate the changes of the central part of the cornea induced by the Ferrara ICRS. They were represented as 3-mm K1, 3-mm K2, and 3-mm Kcyl, similar to the sim K values (Fig 1).

### ANALYSIS OF VISUAL FUNCTION

The OPD map is the spatially resolved refractive state of the eye over the entrance pupil, as displayed by a color-coded map, which is calibrated in diopters, as indicated on adjacent graded color scale. It roughly corresponds to the manifest refraction of the examined eye. Total OPD was measured including the cylinder and its axis. To assess the homogeneity of the refraction over the measured area, OPD values at 3 and 5 mm were recorded and all OPD values were compared (Fig 2).

Root-mean-square (RMS) of the OPD map was recorded in diopters as a global indicator for the image quality. It was measured for the central 3 and 5 mm

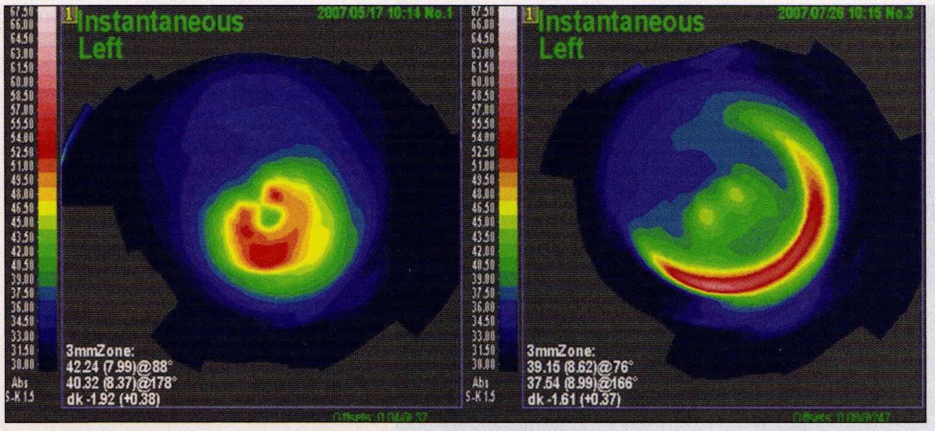



**Figure 1.** Instantaneous topography maps demonstrating the central 3-mm keratometry values. Preoperative (left) showing a peripheral cone (type I). Postoperative (right) after implantation of one Ferrara intracorneal ring segment of 150 $\mu$m (incision at 60°), showing three zones: mild central steepness (residual cone), peripheral hot ring (the segments), and flat intermediate zone.

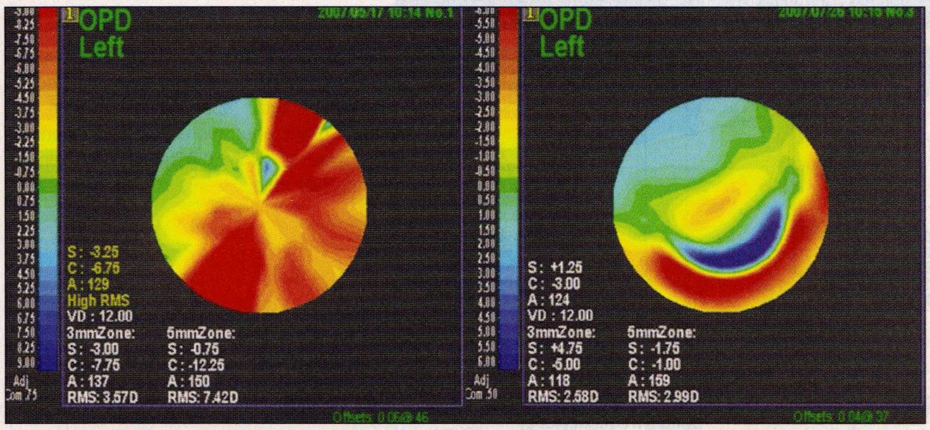



**Figure 2.** Preoperative (left) and postoperative (right) OPD maps (same patient as in Figure 1). Note the hyperopic shift and marked improvement in the central part.

separately to simulate photopic and mesopic conditions (see Fig 2).

Zernike coefficients represent a detailed analysis of the aberrations produced by the optical system. The vertical set of coefficients as measured by the machine was recorded—total aberrations, tilt (represents the prismatic effect), higher order aberrations, total coma, total trefoil, total tetrafoil, total spherical aberration, and higher order astigmatism.

The point spread function (PSF) is represented by the Strehl ratio (Fig 3). The modulation transfer function (MTF) is constructed as two- or three-dimensional diagrams. It can also be represented by a graph. For statistical analysis, the A/D ratio extracted from the graph was recorded. The A/D ratio is the ratio between two areas on that graph. Area A is the area enclosed by the Ave curve (of the patient eye), horizontal and vertical axes. Area D is enclosed between the D curve (diffraction limit), horizontal and vertical axes (Fig 4). The PSF and MTF were subdivided into total and higher order values.

Aberrometry data could be evaluated as either OPD (total eye system) or separated into corneal (anterior corneal surface) and internal (the entire optical system behind the anterior corneal surface, mainly the lenticular component). The Zernike coefficients, Strehl ratio of PSF, and A/D ratio of the MTF were taken for the cornea only to exclude the effect of internal optics.

For each examination, photopic and mesopic pupil diameters were measured in millimeters.

Means of the previous data were calculated, compared, and correlated to each other when appropriate. Preoperative data were compared to the control group to assess the difference between "normal" and keratoconic corneas. Preoperative data were compared to postoperative values to assess the change induced by the Ferrara ICRS. Postoperative values were compared to the control group to determine whether these recovered normal parameters.

## Statistical Analysis

Statistical analysis was done using SPSS software V.10 (SPSS Inc, Chicago, Illinois). Descriptive statistics were expressed in terms of mean±standard deviation (range).

Analytical statistics were expressed using the paired $t$ test to compare pre- and postoperative data. The unpaired $t$ test was used to compare preoperative data and control and postoperative data and control. Correlation matrix and coefficient of correlation with

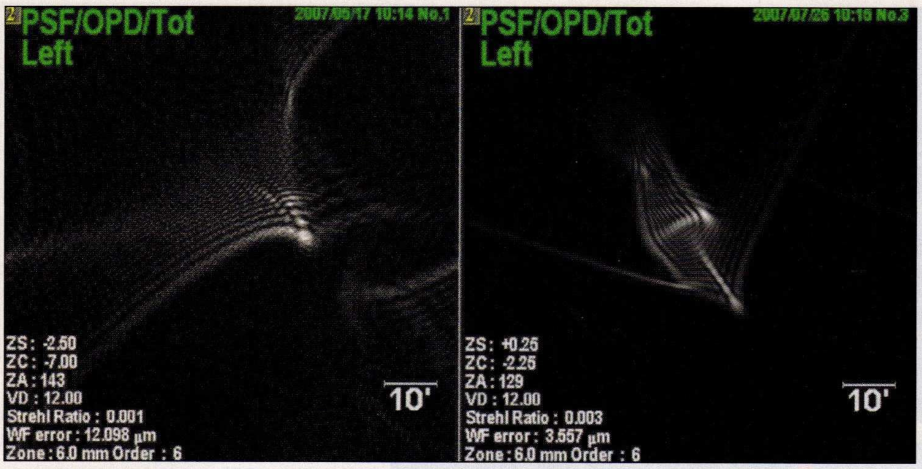



**Figure 3.** Preoperative (left) and postoperative (right) point spread function (PSF) of total aberrometry (higher and lower order aberrations) (same patient as in Figure 1). Note the improvement in the area of the image, Strehl ratio, and wavefront error.

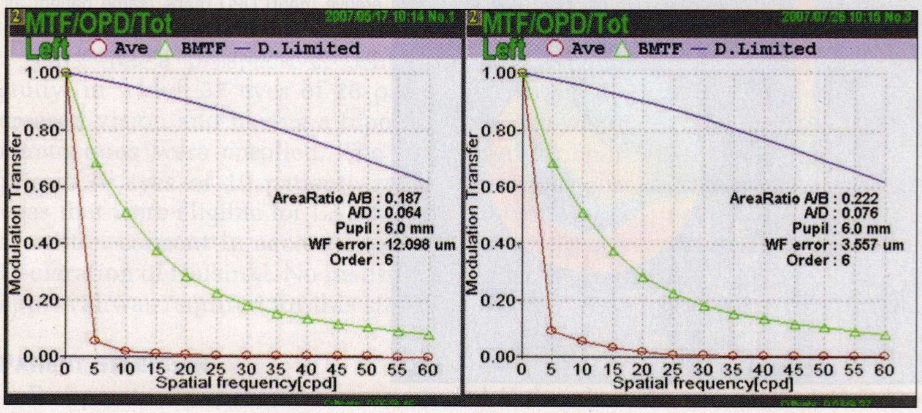



**Figure 4.** Preoperative (left) and postoperative (right) modulation transfer function (MTF) of total aberrometry (higher and lower order aberrations) (same patient as in Figure 1). Note the minor improvement in the A/D ratio.

Pearson's method ($r^2$) was used to correlate two variables in the same group. Chi-square test was used for qualitative data.

A $P$ value <.05 was significant and a value <.01 was highly significant.

## RESULTS

Both groups were matched in age, gender, and eye distribution (Table 2). Photopic and mesopic pupil diameters were also matched (Table 2). The mean interval between the procedure and postoperative examination was 2.96±2.33 months (range: 1 to 9 months). Figures 1-4 present the topography, OPD maps, PSF, and MTF of one representative eye. Distribution according to type of cone centration and number and thickness of Ferrara ICRS used are shown in Figures 5 and 6, respectively. Comparison was first made between keratoconic and non-keratoconic eyes to assess the deviation from normal. Values postoperatively were then compared to preoperative data to evaluate the change induced by the segment(s) implantation. Postoperative values were compared to non-keratoconic eyes to determine whether complete recovery occurred (Tables 3-6).

### Corneal Surface Analysis

Except for the flat meridian at 3 mm (3-mm K2), there was a highly significant statistical difference between normal and keratoconic corneas ($P$<.01). Postoperatively, all parameters improved except for the cylinder value at 3 mm (3-mm Kcyl) ($P$>.05). However, only the flat sim K value (sim K2) improved to a normal value ($P$>.05) (Table 3).

### Visual Function Analysis

*OPD Measurements.* A statistically significant difference was noted between the keratoconic eyes before surgery and the control group regarding the spherical value of the total OPD and OPD at 3 mm ($P$<.05). No statistical difference was found in spherical value of OPD at 5 mm ($P$>.05). A highly significant difference was found at the cylindrical value of all three OPD measurements ($P$<.01) (Table 4).

Postoperatively, spherical and cylindrical values improved ($P$<.01), except for cylinder measured at 5 mm. However, these values did not recover to "normal" (control) values ($P$<.01) (Table 4).

Another analysis was done for the OPD values to

TABLE 2

## Demographic Data for Eyes With Keratoconus and Normal Control Eyes

| Demographic | Keratoconic Eyes | Normal Eyes | *P* Value |
|---|---|---|---|
| Age (y)* | 25.35±6.42 (12 to 44) | 26.74±4.08 (19 to 36) | >.05 |
| Gender (M/F, %) | 20 (54.1)/17 (45.9) | 20 (45.9)/18 (47.4) | >.05 |
| Eye (OD/OS, %) | 17 (45.9)/20 (54.1) | 19 (50)/19 (50) | >.05 |
| Photopic pupil (mm)* | 4.37±0.98 (2.69 to 6.53) | 4.34±0.85 (2.82 to 6.01) | >.05 |
| Mesopic pupil (mm)* | 6.26±1.15 (3.75 to 8.93) | 6.33±0.79 (4.7 to 8.04) | >.05 |

*OD = right eye, OS = left eye*
**Values represented as mean±standard deviation (range).*

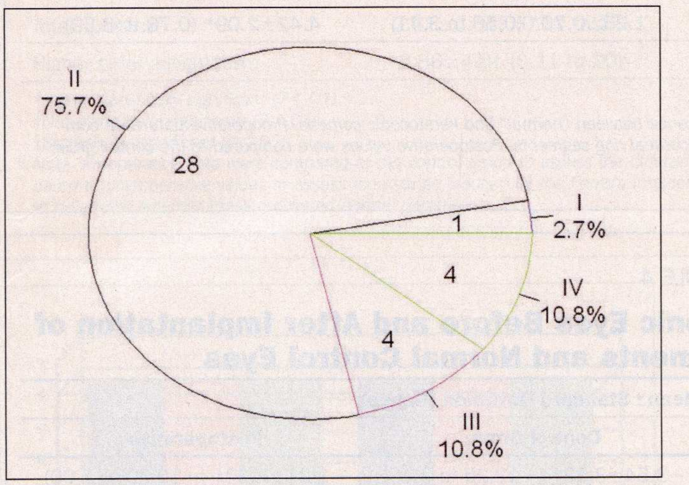



**Figure 5.** Distribution of eyes according to cone centration (in respect to the steep meridian: I being totally peripheral cones and IV being the most central cones).

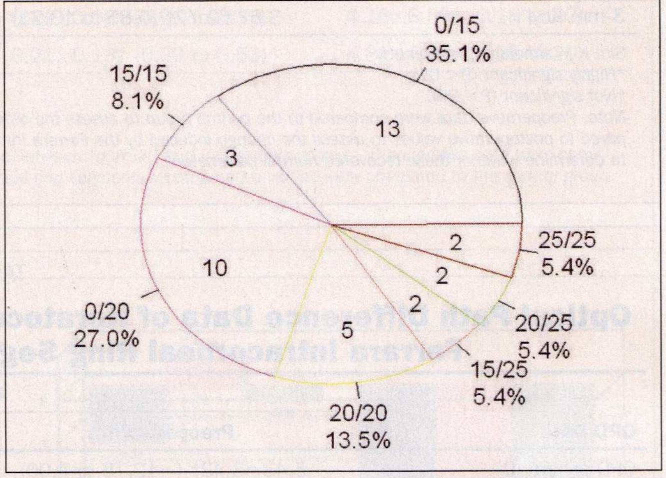



**Figure 6.** Distribution of eyes according to number and thickness of segment(s) implanted. Numbers present thickness of segments in fraction of millimeters (ie, 0.15, 0.20, and 0.25).

assess the homogeneity of the refraction over the measured area.

In keratoconic eyes (preoperative), the spherical value of the total OPD corresponded to the central 3 mm ($P>.05$). However, the values did not compare to the value of OPD at 5 mm ($P<.01$). On the contrary, the cylindrical value of OPD measurements did not correspond ($P<.01$). Only the mean of the axes was nearly the same ($P>.05$) (Fig 7).

Postoperatively, no statistical difference was noted between all OPD values in the same eye, ie, sphere, cylinder, and mean of axes ($P>.05$). A highly significant statistical difference was present between the sphere of total OPD and sphere of OPD at 3 mm ($P<.01$) (Fig 7).

In the control group, a highly significant difference was noted between spherical values ($P<.01$), but no difference was found concerning the cylinder and mean of the axes ($P>.05$) (see Fig 7).

*Optical Path Difference RMS Values.* A highly significant statistical difference was found between the keratoconic eyes and control group at 3 and 5 mm ($P<.01$). No difference was found before and after surgery ($P>.05$). In the keratoconic eyes (before and after surgery) and control group, a highly significant difference was noted between RMS measured at 3 and 5 mm ($P<.01$) (Table 4).

*Zernike Coefficients.* A highly significant statistical difference was found between keratoconic eyes and the control group in all coefficients ($P<.01$). For the higher order aberrations, the coefficient with the highest amplitude was coma, followed by trefoil, tetrafoil, higher order astigmatism, and spherical aberration. Postoperatively, a statistically insignificant increase in amplitude occurred in all coefficients, maintaining the same order ($P>.05$). Total aberrations and tilt improved statistically significantly ($P<.01$). This improvement did not recover to "normal" (control) values ($P>.05$) (Table 5).

*Point Spread Function and Modulation Transfer Function.* A highly significant statistical difference was found between keratoconic and "normal" (control) corneas ($P<.01$) concerning the PSF and MTF values, both for total and higher order aberrations. There was

TABLE 3

**Topographic Data of Keratoconic Eyes Before and After Implantation of Ferrara Intracorneal Ring Segments and Normal Control Eyes**

| | Mean±Standard Deviation (Range) | | |
|---|---|---|---|
| **Topographic Data** | **Preoperative** | **Control Group** | **Postoperative** |
| Sim K1 | 52.95±5.95* (12 to 44) | 44.03±1.62* (41.11 to 46.49) | 46.29±3.04* (40.27 to 53.15) |
| Sim K2 | 46.8±3.16* (43.44 to 67.65) | 42.96±1.34* (40.13 to 44.82) | 43.46±2.91† (38.18 to 50.00) |
| Sim Kcyl | 6.14±3.10* (1.67 to 16.89) | 1.07±0.63* (0.28 to 2.41) | 2.84±1.77* (0.13 to 6.66) |
| Avg K | 50.17±3.64* (42.87 to 58.00) | 43.49±1.44* (40.64 to 45.59) | 46.41±3.10* (41.07 to 53.65) |
| 3-mm K1 | 45.82±2.70* (40.81 to 52.98) | 43.77±1.47* (40.86 to 46.42) | 41.15±5.47* (22.80 to 54.79) |
| 3-mm K2 | 41.61±4.44* (20.32 to 49.13) | 42.55±1.35† (39.61 to 44.7) | 36.71±5.47* (18.68 to 47.27) |
| 3-mm Kcyl | 3.67±2.72† (0.85 to 13.21) | 1.23±0.70* (0.16 to 3.41) | 4.42±2.09* (0.78 to 8.59) |

*Sim K = simulated keratometry*
**Highly significant (P<.01).*
*†Not significant (P>.05).*
*Note. Preoperative data were compared to the control group to assess the difference between "normal" and keratoconic corneas. Preoperative data were compared to postoperative values to assess the change induced by the Ferrara intracorneal ring segments. Postoperative values were compared to the control group to determine whether these recovered normal parameters.*

TABLE 4

**Optical Path Difference Data of Keratoconic Eyes Before and After Implantation of Ferrara Intracorneal Ring Segments and Normal Control Eyes**

| | Mean±Standard Deviation (Range) | | |
|---|---|---|---|
| **OPD Data** | **Preoperative** | **Control Group** | **Postoperative** |
| OPD sphere (D) | −5.43±3.43* (−12.75 to 4.00) | −3.54±3.13† (−12.25 to 3.75) | −1.27±4.30† (−10.50 to 7.00) |
| OPD cylinder (D) | −6.33±3.30* (−16.00 to −1.00) | −0.94±0.62* (−2.50 to 0) | −3.26±2.45* (−10.50 to −0.50) |
| OPD axis (°) | 102.97±60.43‡ (9 to 176) | 100.5±66.69‡ (1 to 180) | 84.70±57.12‡ (1 to 180) |
| OPD 3-mm sphere (D) | −5.29±3.11* (−11.00 to 2.75) | −3.44±3.15† (−12.25 to 3.75) | 0.68±3.37* (−7.75 to 5.75) |
| OPD 3-mm cylinder (D) | −5.39±2.82* (−13.25 to −0.75) | −0.80±0.80* (−2.75 to 0) | −2.48±2.86* (−6.25 to 5.75) |
| OPD 3-mm axis (°) | 101.67±61.59† (7 to 176) | 93.52±67.96‡ (3 to 179) | 76.48±46.69‡ (4 to 179) |
| OPD 5-mm sphere (D) | −3.97±2.52* (−8.00 to 2.25) | −3.20±2.78‡ (−10.50 to 3.50) | −0.33±3.76* (−5.00 to 13.25) |
| OPD 5-mm cylinder (D) | −3.95±2.32‡ (−12.25 to −0.50) | −0.81±0.80* (−2.75 to 0) | −3.79±5.17* (−14.25 to 16.50) |
| OPD 5-mm axis (°) | 96.38±71.67‡ (1 to 179) | 85.71±62.64‡ (7 to 179) | 99.45±67.69‡ (4 to 180) |
| RMS 3-mm (D) | 2.34±1.16‡ (0.36 to 4.53) | 0.25±0.14* (0.10 to 0.73) | 2.07±1.08* (0.38 to 4.49) |
| RMS 5-mm (D) | 3.38±1.71‡ (0.29 to 7.42) | 0.33±0.16* (0.09 to 0.89) | 4.16±2.89* (0.79 to 14.08) |

*OPD = optical path difference, RMS = root-mean-square*
**Highly statistically significant (P<.01).*
*†Statistically significant (P<.05).*
*‡Not statistically significant (P>.05).*
*Note. Preoperative data were compared to the control group to assess the difference between "normal" and keratoconic corneas. Preoperative data were compared to postoperative values to assess the change induced by the Ferrara intracorneal ring segments. Postoperative values were compared to the control group to determine whether these recovered normal parameters.*

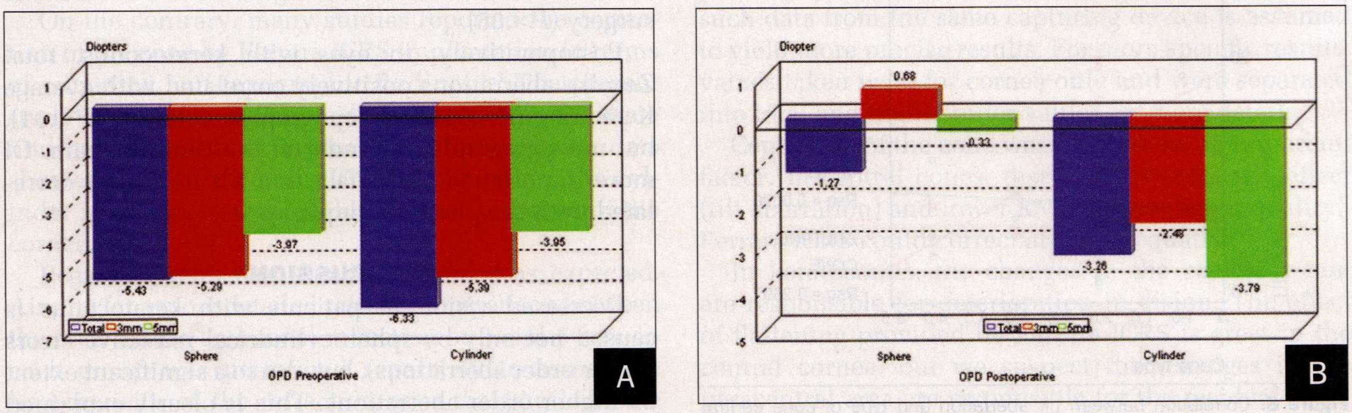
no difference in these values between keratoconic eyes before and after surgery ($P$>.05). Preoperatively, there was a highly significant difference between total and higher order MTF ($P$<.01). No difference was found for theses values after surgery ($P$>.05). In addition, no difference was found between total and higher order PSF before or after surgery ($P$>.05). However, in the control group, a highly significant statistical difference was found between total and higher order PSF and MTF ($P$<.01) (Table 6).

TABLE 5

**Zernike Coefficients in Keratoconic Eyes Before and After Implantation of Ferrara Intracorneal Ring Segments and Normal Control Eyes**

| | Mean±Standard Deviation (Range) | | |
|---|---|---|---|
| Aberration | Preoperative | Control Group | Postoperative |
| Total | 14.82±4.84* (5.42 to 20) | 2.05±0.52† (1.26 to 3.51) | 12.25±5.57† (4.02 to 20) |
| Tilt | 11.77±5.41* (2.28 to 20) | 0.92±0.51‡ (0.05 to 2.34) | 8.20±5.38† (1.27 to 20) |
| Higher order | 7.53±6.03† (0.96 to 20) | 0.80±0.3† (0.33 to 1.6) | 8.23±7.42† (1.66 to 20) |
| Total coma | 5.46±4.64† (0.80 to 20) | 0.39±0.19† (0.06 to 0.77) | 6.17±6.69† (0.82 to 20) |
| Total trefoil | 3.51±4.56† (0.09 to 20) | 0.48±0.28† (0.06 to 1.16) | 5.43±7.3† (0.44 to 20) |
| Total tetrafoil | 2.95±5.12† (0.11 to 20) | 0.22±0.14† (0.30 to 0.54) | 4.85±6.97† (0.05 to 20) |
| Total spherical | 2.21±4.08† (0.12 to 20) | 0.24±0.08† (0.01 to 0.39) | 4.16±6.59† (0.18 to 20) |
| Higher order astigmatism | 2.56±4.8† (0.11 to 20) | 0.21±0.13† (0.20 to 0.53) | 4.81±6.93† (0.29 to 20) |

**Highly statistically significant (P<.01).*
*†Not statistically significant (P>.05).*
*‡Statistically significant (P<.05).*
*Note. Preoperative data were compared to the control group to assess the difference between "normal" and keratoconic corneas. Preoperative data were compared to postoperative values to assess the change induced by the Ferrara intracorneal ring segments. Postoperative values were compared to the control group to determine whether these recovered normal parameters.*



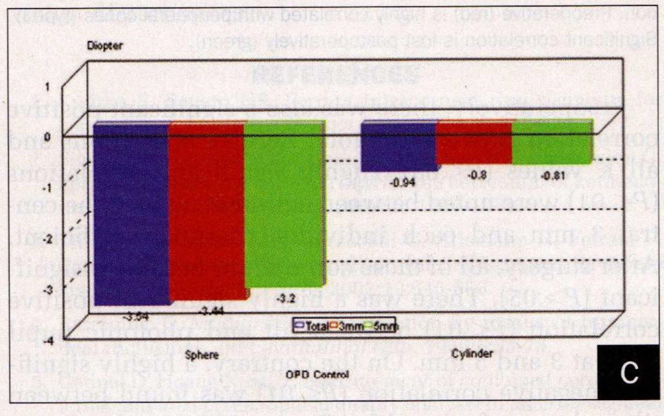




**Figure 7.** Graphs comparing means of data extracted from the OPD map (as in Figure 2), showing the homogeneity of the refraction in each group. Note the **A)** central myopia in keratoconus in comparison to **B)** central flatness after Ferrara intracorneal ring segment implantation, and **C)** homogenous refraction over the pupil in "normal" individuals.

Correlations were performed between different measured values. A large series of statistically significant correlations resulted. Only the most relevant correlations are presented.

In keratoconic eyes before surgery, there was a highly significant positive correlation between the average K readings and topographic cylinder ($P<.01$). After the procedure, this significance was lost ($P>.05$).

TABLE 6

**Point Spread Function and Modulation Transfer Function Data of Keratoconic Eyes Before and After Implantation of Ferrara Intracorneal Ring Segments and Normal Control Eyes**

| | Mean±Standard Deviation (Range) | | |
|---|---|---|---|
| **Data** | **Preoperative** | **Control Group** | **Postoperative** |
| Total PSF (Strehl ratio) | 0.0022±0.0036* (0 to 0.02) | 0.01±0.005† (0.003 to 0.026) | 0.0031±0.0052* (0 to 0.032) |
| Higher order PSF (Strehl ratio) | 0.0033±0.0045* (0 to 0.02) | 0.01±0.009† (0.004 to 0.044) | 0.0029±0.005* (0 to 0.3) |
| Total MTF (A/D) | 0.064±0.008* (0.055 to 0.101) | 0.11±0.03† (0.013 to 0.182) | 0.068±0.011† (0.055 to 0.108) |
| Higher order MTF (A/D) | 0.07±0.01* (0.05 to 0.12) | 0.14±0.044† (0.022 to 0.229) | 0.068±0.011† (0.055 to 0.107) |

*PSF = point spread function, MTF = modulation transfer function, A/D = ratio of area enclosed by the Ave curve (of the patient eye) and area enclosed between the D curve (diffraction limit)*
**Not statistically significant (P>.05).*
*†Highly statistically significant (P<.01).*
*Note. Preoperative data were compared to the control group to assess the difference between "normal" and keratoconic corneas. Preoperative data were compared to postoperative values to assess the change induced by the Ferrara intracorneal ring segments. Postoperative values were compared to the control group to determine whether these recovered normal parameters.*

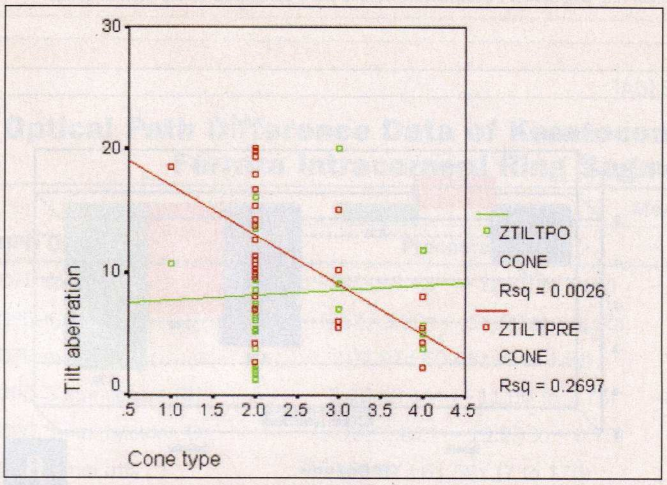



**Figure 8.** Correlation between tilt aberration and type of cone centration. Preoperative (red) is highly correlated with peripheral cones (type I). Significant correlation is lost postoperatively (green).

Preoperatively, there was also a significant positive correlation between the total Zernike aberrations and all K values ($P<.05$). Highly significant correlations ($P<.01$) were noted between cylinder value at the central 3 mm and each individual Zernike coefficient. After surgery, all of these correlations became insignificant ($P>.05$). There was a highly significant positive correlation ($P<.01$) between tilt and photopic pupil RMS at 3 and 5 mm. On the contrary, a highly significant negative correlation ($P<.01$) was found between tilt and type of cone. After Ferrara ICRS implantation, the significance in correlation between tilt and type of cone was lost ($P>.05$). In addition, the correlation between photopic pupil RMS at 3 and 5 mm was lost ($P>.05$) (Figs 8 and 9).

Highly significant negative correlations ($P<.01$) were noted between the type of cone and RMS values at 3 and 5 mm; however, this significance was lost after surgery ($P>.05$).

Postoperatively, in eyes with keratoconus, total Zernike aberrations positively correlated with average K reading ($P<.01$) and topographic cylinder ($P<.01$), but not topographic cylinder at the central 3 mm. Of more importance is the fact that tilt no longer correlated with the photopic pupil.

## DISCUSSION

Decreased vision in patients with keratoconus is caused not only by spherocylindrical refractive errors (lower order aberrations), but also to a significant extent by higher order aberrations. This is clearly explained by the fact that spectacles, in most cases, are unable to provide full correction. The predominant defect is in the coma aberration, specifically its vertical component,[8-11] which was shown by different studies using different instruments in which the same results were obtained. Alió and Shabayek[11] used this property to modify the classic Amsler-Krumeich classification for keratoconus, making the amount of coma aberration one of the parameters.

The presence of night visual symptoms after implantation of different types of ICRS questioned the extent to which they actually correct the condition. Chalita and Krueger[8] presented one case before and after implantation of Ferrara ICRS. Their study showed an increase in the amount of total higher order aberration, coma aberration (with loss of vertical orientation), spherical aberration, and predominance of the quadrafoil component. However, the same study showed im-

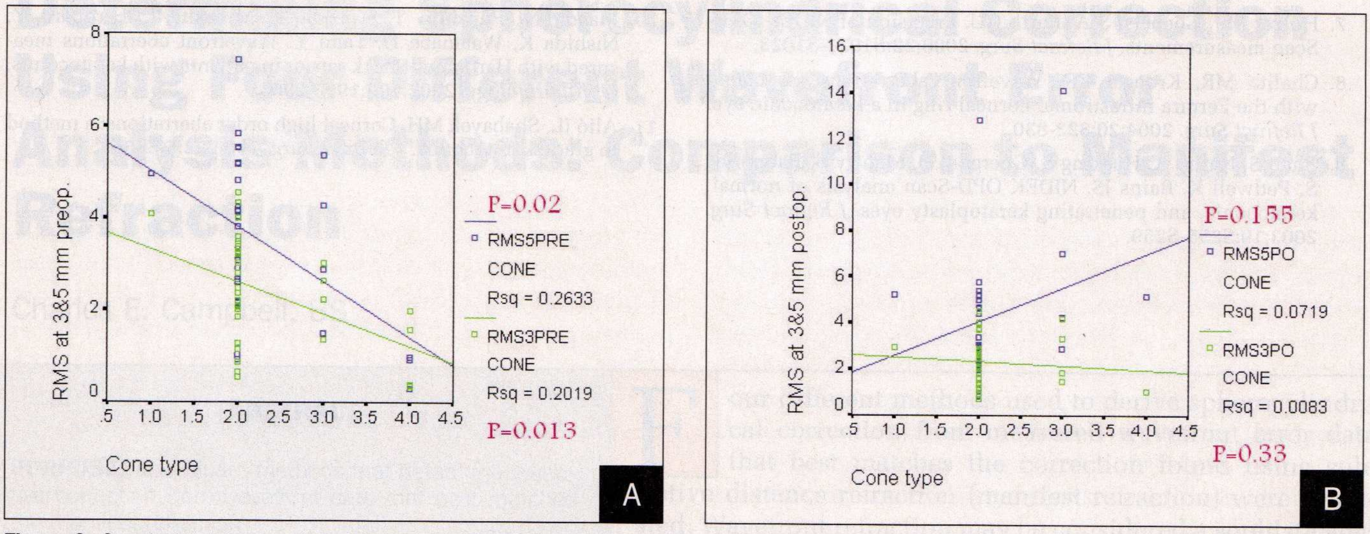



**Figure 9.** Correlation between root-mean-square (RMS) values of the OPD map at 3 and 5 mm (RMS3 and RMS5, respectively) and type of cone centration (as for Figures 5 and 8) is **A)** significant preoperatively and **B)** not significant postoperatively.

provement in convoluted PSF and MTF. After an extensive Internet search, no other studies were found that addressed this issue.

On the contrary, many studies reported the correction of the cone by Ferrara ICRS implantation in terms of refraction and topographic findings.[1-3] The present study confirms, by a simple data comparison, the same findings. In addition, evaluation of topographic data showed that, after Ferrara ICRS implantation, the cylinder is no longer responsible for the steepness of the cornea.

Regarding refraction, it also improved as expected. Aiming for a more detailed result, a comparison between the total values and zonal refraction at 3 and 5 mm in each group was performed separately to assess the homogeneity of the refraction over the pupil. In the control group, with normal prolate corneas, the sphere in the total pupil corresponded to that in the central 3 mm with a slight decrease at the 5-mm zone. The cylinder, however, was the same. In eyes with hyperprolate keratoconus, even the cylinder did not match.

After implantation, all spherical and cylinder data became homogenous, except for the central 3 mm sphere, which was more hyperopic. This shows that the effect of flattening of the Ferrara ICRS is more evident at the central part. An additional finding supporting this conclusion is that the central 3-mm cylinder is no longer responsible for the residual aberrations.

Although refraction (OPD values) improved, RMS did not. This is explained by the persistence of higher order aberrations. The same reason explains the maintenance of low PSF and MTF values.

In this study, PSF and MTF were evaluated directly from the system and not via intermediate software. Previous studies[8] analyzed PSF and MTF by capturing wavefront and topography maps separately, and then processing them with analyzing software. Retrieving such data from the same capturing device is assumed to yield more precise results. For more specific results, values taken were for cornea only and were separated into total and higher order values for more details.

Centration of the cone was found to be an important factor. In central cones, there is less prismatic effect (tilt aberration) and lower RMS values (better quality). Ferrara ICRS could correct all types equally.

In keratoconus, the changes in the central 3 mm are responsible for deterioration in vision. The effect of flattening provided by Ferrara ICRS is great in the central cornea, but we suspect that changes in the paracentral area are responsible for the residual night vision disturbances.

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