Change of optical quality with Intraocular lens implantation: Corneal aberrations

7

7. Change of optical quality with IOL implantation: corneal aberrations

This chapter is based on the article by S.Marcos et al. *"Change in corneal aberrations after cataract surgery with 2 types of aspherical intraocular lenses"* Journal of Cataract Refractive Surgery Vol 33, 217226-1067. Coauthors of the study are Lourdes Llorente, Ignacio Jiménez-Alfaro and Patricia Rosales. The contribution of Patricia Rosales to the study was participation in data collection, processing and analysis of corneal aberrations of patients.

RESUMEN

Objetivos: Estudiar el efecto de la incisión corneal sobre las aberraciones corneales en pacientes operados de cirugía de cataratas, con dos tipos de lentes intraoculares (LIO) monofocales, de diseño asférico.

Métodos: Se toman topografías corneales en 43 ojos, antes y después de la cirugía de cataratas con incisión corneal superior. Veinte y dos ojos fueron implantados con una lente intraocular asférica de silicona (Tecnis Z9000, Advanced Medical Optics) y veinte y un ojos una lente intraocular asférica acrílica (AcrySof IQ SN60WF, Alcon Research Labs) empleando el tipo de inyector recomendado para cada tipo de LIO. El tamaño de la incisión corneal (3.2 mm) fue similar en los dos grupos. Las aberraciones corneales se evaluaron empleando algoritmos propios (basados en trazados de rayos) para tamaños de pupila de 10.0 y 5.0 mm. Las comparaciones entre medidas pre-cirugía y post-cirugía y entre grupos se realizó para términos de Zernike individuales y para el error cuadrático medio (RMS) del frente de onda.

Resultados: La RMS (excluyendo prisma y desenfoque) del grupo con la LIO AcrySof IQ no cambió, incrementando en cambio para el grupo de las LIO Tecnis para diámetros de pupila de 10.0 y 5.0 mm. La aberración esférica, y términos de coma, no cambiaron significativamente; sin embargo, el astigmatismo vertical, trefoil vertical y tetrafoil vertical cambiaron significativamente con la cirugía para ambos diámetros de pupila de 10.0 y 5.0 mm (P<.0005) en ambos grupos. El patrón de aberraciones de onda inducido para aberraciones de tercer orden y superior mostraban un lóbulo superior, como consecuencia de una combinación de trefoil vertical positivo (Z_3^{-3}) y tetrafoil negativo (Z_4^4). El astigmatismo vertical promedio se incrementó en 2.47 μm ± 1.49 (SD) y 1.74 ± 1.44 μm, el trefoil vertical se incrementó en 1.81 ± 1.19 μm y 1.20 ± 1.34 μm, y el tetrafoil se incrementó en -1.10 ± 0.78 μm y -0.89 ± 0.68 μm en los grupos Tecnis y AcriSof IQ, respectivamente.

Conclusiones: No se observan diferencias significativas entre las aberraciones corneales post-cirugía en los dos grupos, aunque hubo más términos u órdenes que cambiaron de modo significativo estadísticamente en el grupo de LIO Tecnis, para el que se encontraron que las aberraciones inducidas eran ligeramente mayores.

ABSTRACT

Purpose: To study the effect of cataract surgery (through 3.2-mm superior incisions) on corneal aberrations with 2 types of monofocal intraocular lenses (IOLs) with aspherical designs.

Methods: Corneal topography of 43 eyes was obtained before and after small corneal incision cataract surgery. Twenty-two eyes had implantation of a Tecnis Z9000 silicone IOL (Advanced Medical Optics) and 21 had implantation of an AcrySof IQ SN60WF acrylic IOL (Alcon Research Labs) using the recommended injector for each IOL type. The intended incision size (3.2 mm) was similar in the two groups. Corneal aberrations were estimated using custom-developed algorithms (based on ray tracing) for 10.0 mm and 5.0 mm pupils. Comparisons between preoperative and postoperative measurements and across the groups were made for individual Zernike terms and root-mean-square (RMS) wavefront error.

Results: The RMS (excluding tilt and defocus) did not change in the AcrySof IQ group and increased significantly in the Tecnis group with the 10.0 mm and 5.0 mm pupil diameters. Spherical aberration and coma-like terms did not change significantly; however, vertical astigmatism, vertical trefoil, and vertical tetrafoil changed significantly with surgery with the 10.0 mm and 5.0 mm pupil diameters (P<.0005). The induced wave aberration pattern for 3rd-and higher-order aberrations consistently showed a superior lobe, resulting from a combination of positive vertical trefoil (Z_3^{-3}) and negative tetrafoil (Z_4^4). The mean vertical astigmatism increased by 2.47 µm± 1.49 (SD) and 1.74 ± 1.44µm, , vertical trefoil increased by 1.81 ± 1.19µm and 1.20 ± 1.34 µm, and tetrafoil increased by -1.10 ± 0.78 µm and -0.89 ± 0.68 µm in the Tecnis group and AcrySof IQ group, respectively.

Conclusions: There were no significant differences between the corneal aberrations in the 2 postoperative groups, although there was a

tendency toward more terms or orders changing statistically significantly in the Tecnis group, which had slightly higher amounts of induced aberrations.

1. INTRODUCTION

Cataract surgery has advanced considerably in the past few years. Among other advances, foldable intraocular lenses (IOLs) allow implantation through small incisions and more sophisticated optical surfaces give better control of optical outcomes. In particular, monofocal IOLs with aspherical surfaces (resulting in negative spherical aberration) have been introduced with the aim of balancing the positive corneal spherical aberration (Holladay, Piers, Koranyi, van der Mooren & Norrby, 2002). These IOLs reduce the amount of spherical aberration with respect to conventional spherical IOLs (Marcos, Barbero & Jiménez-Alfaro, 2005, Padmanabhan, Rao, Jayasree, Chowdhry & Roy, 2006), and some studies have shown contrast sensitivity improvements over the spherical IOLs (Mester, Dillinger & Anterist, 2003, Packer, Fine, Hoffman & Piers, 2004).

Higher-order aberrations (HOAs) of the cornea (i.e., 3^{rd} and higher order terms), and the geometry and positioning of the IOL, all contribute to final optical quality. The benefit of correcting spherical aberration relies on relative small contribution of other factors that potentially increasing HOAs (Marcos, Burns, Prieto, Navarro & Baraibar, 2001); these include lens tilt and decentration (Rosales & Marcos, 2006), and corneal irregularities.

Several studies (Jacobs, Gaynes & Deutsch, 1999, Rainer, Menapace, Vass, Annen, Findl & Schmetter, 1999) have discussed the potential role of the corneal incision in altering corneal shape. It is well known that the corneal incision modifies corneal astigmatism by about 1.00 diopter (D), and the location of the incision is often created in the steepest meridian with the aim of reducing corneal astigmatism. Hayashi et al (Hayashi, Hayashi, Oshika & Hayashi, 2000) evaluated irregular astigmatism using Fourier analysis of corneal elevation maps from videokeratography preoperatively and after implantation of silicone, acrylic and poly(methyl methacrylate) (PMMA) IOLs through 3.5 mm, 4.1 mm and 6.5 mm incisions in 240 eyes. They found that "high-order irregularities" increased after surgery in all three groups, but this increase persisted 3 months after surgery only in the 6.5 mm group. Guirao (Guirao, Redondo, Geraghty, Piers, Norrby & Artal, 2002) performed one of the first studies reporting corneal aberrations after cataract surgery (extracapsular cataract extraction with a 6.0 mm incision and PMMA IOL implantation). A comparison with corneal aberrations in a healthy age-matched control group (20 eyes in each group) showed no statistically significant differences for 4.0 mm pupil diameters. Barbero (Barbero, Marcos & Jimenez-Alfaro, 2003) studied total and corneal aberrations in 9 eyes after cataract surgery (phacoemulsification with implantation of acrylic spherical IOLs through a 4.1 mm incision). They found slightly higher (but not statistically significant) corneal aberrations in postoperative eyes than in a young control group (for 5.0 mm); however, all eyes measured preoperatively and postoperatively showed larger amounts of 3rd and higher order corneal aberrations after surgery. One of the most comprehensive studies of changes in corneal aberrations after small-incision cataract surgery is that of Guirao (Guirao, Tejedor & Artal, 2004). They measured corneal aberrations (for 6.0 mm pupils) in the same eyes before and after implantation of monofocal foldable spherical IOLs (silicone and acrylic) through a 3.5 mm superior, nasal or temporal incision. Although a major conclusion was that a small incision does not systematically degrade anterior corneal optical quality, there were changes in some aberrations and a significant increase in astigmatism and trefoil.

The amount and orientation of the aberrations induced depended on the surgical meridian. Pesudovs (Pesudovs, Dietze, Stewart & Cox, 2005) studied the effect of two types of spherical IOLs (PMMA and acrylic) and incision locations (corneal and scleral) on total wave aberrations measured with a Hartmann-Shack wavefront sensor. Aberrations in 20 eyes (PMMA IOL, scleral incision), 21 (acrylic IOL, scleral incision), and 16 (acrylic IOL, corneal incision), were compared with those in an age-matched control group. The authors found that scleral incisions induced fewer aberrations than corneal incisions. The PMMA-scleral group (incision size of 5.2 mm) had fewer aberrations than the acrylic-corneal group (incision size 3.5 mm), and aberrations comparable to those in the control group. They report higher amounts of total tetrafoil in the acrylic-corneal group than in the phakic group.

In this chapter, we report corneal aberrations over 10.0 mm and 5.0 mm diameters in patients who had implantation of recently introduced aspherical IOLs (Tecnis, Z9000, Advanced Medical Optics; Acrysof IQ, SN60WF, Alcon Research Labs). By measuring aberrations over a large pupil diameter, we were able to assess to a greater extent the optical changes produced on the anterior cornea, not limited by the eye´s pupil size. This analysis is relevant in the understanding of corneal biomechanical changes after an incision, and in the assessment of off-axis optical quality. We also present data for 5.0 mm pupils to account for changes potentially more relevant to visual function. The surgical protocol was identical in all eyes, including incision size (3.2 mm) and location (superior), to avoid confounding factors associated with differences in incision architecture. In this context, the purposes of this work were to assess (1) whether there is a systematic increase in corneal aberrations after small-incision cataract surgery and obtain an average map of induced corneal aberrations with this procedure; (2) whether there are corneal differences associated with the type of IOL implanted. This information will be of great use to simulate surgical outcomes using eye models (in which the average map of induced aberrations can be incorporated), in understanding optical performance in eyes implanted with IOLs, particularly with new designs aiming at reducing the amount of aberrations, and in evaluating which aspects of surgery should be improved. This information will be used in Chapter 8 where the performance of customized model eyes is compared to real measurements of ocular aberrations in pseudophakic eyes with aspheric IOLs.

2. METHODS

2.1 Patients:

Forty-three eyes of twenty-three patients with cataract were studied. Patient were invited to participate in the study and to randomly have bilateral implantation of 1 or 2 types of aspherical IOLs (Tecnis, Z9000, Advanced Medical Optics and Acrysof IQ, SN60WF, Alcon Research Labs). Inclusion criteria included good general health, no ocular pathology, astigmatism less than 2.50 D, younger than 75 years old, and no complications after surgery. All patients recruited before surgery completed the study. All enrolled patients were informed of the nature of the study and signed consent forms. Protocols had been approved by Institutional review boards and ethical committees and adhered to the tenets of the Declaration of Helsinki.

Clinical examination at the hospital (Fundación Jiménez Díaz) included best-spectacle corrected (BSCVA), uncorrected visual acuity (UCVA), refractometry, keratometry, ultrasound biometry, tonometry, biomicroscopy and indirect ophthalmoscopy. Corneal diameters were obtained from infrared front illumination images, using custom algorithms of limbus detection and ellipse fitting. Table 1 shows a profile of the patients.

All procedures were performed by the same surgeon (I.J-A.) on an outpatient basis using topical anaesthesia. The same procedure was used to implant both types of IOLs.

A 3.2 mm superior clear corneal incision (approximately 1 mm from the limbus) and a paracentesis were created with a surgical knife. A 6.0 mm continuous curvilinear capsulorhexis was made under an ophthalmic viscosurgical device (OVD). Phacoemulsicationcation of the lens was performed with the Venturi Millenium system (Bausch & Lomb). After the cortical material was removed, the capsules were cleaned with the automatic irrigation/aspiration straight tip. The Tecnis IOL was implanted using the AMO Silver Series II injector, and the Acrysof IQ using the Monarch II injector. Once the OVD was removed, the incision was closed by hydration, without sutures. Postoperatively, patients were treated with a combination dexamethasone and tobramycin for 4 weeks.

Table 7.1. Profile of patients

	Acrysof group (n=21)	**Tecnis group (n=22)**	**p-value**
Age (yr)	71.1±3.0	68.0±9.5	0.174
Pre-operative spherical error (D)	-1.26 ± 2.6	-1.59±2.85	0.712
Pre-operative astigmatism (D)	0.8 ±0.7	1.5 ± 0.7	0.005*
Corneal diameter @ vertical meridian (mm)**	11.1±0.2	11.05±0.58	0.700
Pre-operative Corneal Astigmatism (D)	0.96±0.68	1.17±0.90	0.397
Pre-operative Mean Corneal Power (D)	44.58±1.30	43.92±1.20	0.095
Post-operative Corneal Astigmatism (D)	0.92±0.53	1.26±0.63	0.072
Post-operative Mean Corneal Power (D)	44.60±1.32	43.92±1.28	0.105
IOL power (D)	20.6±2.0	21.3±3.4	0.428
Time between surgery and post-op measurements (days)	115±106	95±64	0.472

IOL= intraocular lens; SE= spherical equivalent.

* Unpaired t-test, *P*<0.05, significantly different with a confidence interval of 95%

**This parameter includes 10 AcrySof eyes and 19 Tecnis eyes as images from the other eyes were inadequate to estimate vertical corneal diameter.

2.2 Anterior corneal aberrations

Corneal topography was measured by videokeratoscopy (Atlas, Humphrey-Zeiss). Elevation maps measured with respect to a reference plane tangential to the corneal vertex were exported as ASCII files to custom software written in Matlab (Mathworks). Aberrations were obtained using the optical design program Zemax (Focus Software, Tucson, AZ), launched from a visual interface programmed in Visual Basic. In brief, corneal ray aberrations were obtained by virtual ray tracing on the anterior corneal surface after which wave aberrations were obtained by modal fitting of ray aberrations to the derivatives of Zernike polynomial expansions up to the 7th order. A detailed description of the techniques has been presented previously (Barbero, Marcos, Merayo-Lloves & Moreno-Barriuso, 2002, Barbero, Marcos & Merayo-Lloves, 2002, Marcos, Barbero, Llorente & Merayo-Lloves, 2001). In the present study, corneal aberrations were obtained for 10.0 mm pupil diameters and referred to the corneal reflex. In addition, the corneal Zernike terms, obtained for 10.0 mm, were re-scaled for 5.0 mm pupils

Corneal topography was obtained preoperatively (fewer than 10 days before surgery) and postoperatively (at least 45 days after surgery). Corneal aberrations are expressed as individual Zernike coefficients (i.e. 4^{th}-order spherical aberration, vertical trefoil), as the root mean square (RMS) of a combination of some terms (i.e. coma-like, trefoil) or as the RMS of Zernike orders (i.e 3^{rd}- and higher-order RMS, 3rd-order RMS). Induced aberrations were obtained as the difference between postoperative and preoperative aberrations for each Zernike term.

2.3 Statistical analysis

Corneal aberrations were compared before and after surgery in both groups of patients, and statistical differences were tested using a paired *t* test for 2-sample comparison. Also, preoperative, postoperative, and induced aberrations were compared across groups, and statistical differences were tested using unpaired *t* test for two sample comparison.

3. RESULTS

Figure 7.1 shows typical examples of corneal wave aberration patterns, before and after surgery, as well as the induced wave aberrations (for 3rd and higher orders; that is, excluding tilt, defocus and astigmatism).

The differences between the postoperative and preoperative patterns were consistent across eyes, with a typical superior lobe in the postoperative pattern that was not present in the preoperative pattern. The position of the lobe was consistent with the superior incision. Looking at individual terms, postoperative patterns showed consistently increased vertical astigmatism Z_2^2, increased vertical trefoil Z_3^{-3} and increased vertical tetrafoil Z_4^4 (toward more negative values). The combination of positive trefoil and negative tetrafoil produces the characteristic superior lobe in the postoperative and induced aberration patterns.

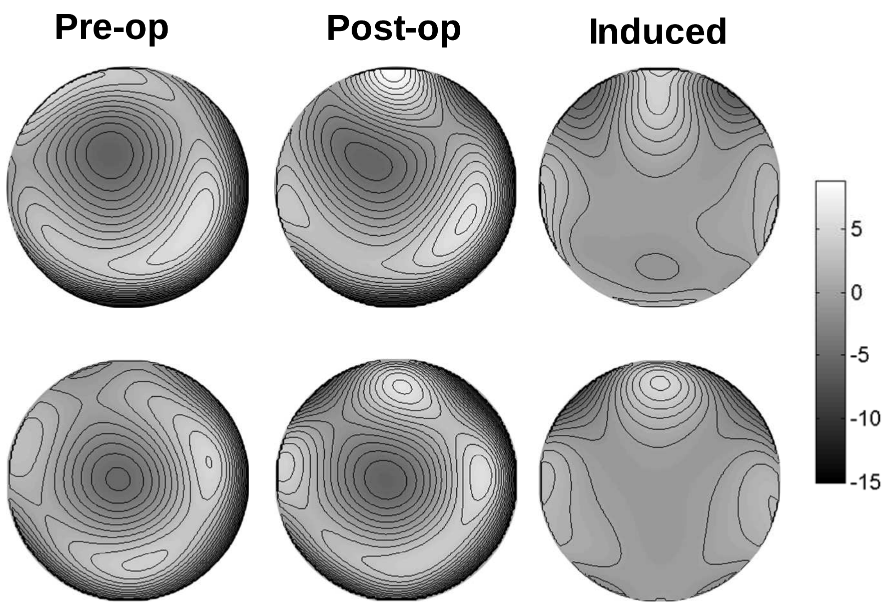

Figure 7.1. Maps of preoperative corneal aberrations, postoperaive corneal aberrations, and induced corneal aberrations (difference between postoperative and preoperative aberrations) in 2 eyes. Top: AcrySof IQ IOL. Bottom: Tecnis IOL. Data are for 3rd-and higher-order aberrations and a 10.0 mm corneal diameter.

Figure 7.2 shows preoperative, postoperative, and induced vertical astigmatism, trefoil, tetrafoil, and spherical aberration in all eyes in each group (10.0 mm). Figure 7.3 shows the RMS, including all terms (except tilt and defocus), in all eyes in each group. Table 2 shows the relevant mean preoperative and postoperative individual Zernike coefficient and RMS (for different orders and terms), for 10.0 and 5.0 mm pupils in the Acrysof IQ group and Tecnis group respectively. Preoperative aberration values, except for vertical coma with a 10.0 mm pupil, were not statistically different between groups. In the Acrysof group, there were statistically significant preoperative and postoperative differences in vertical astigmatism, vertical trefoil and vertical tetrafoil (both for 10 and 5-mm pupils) as well as other 6 and 10 higher order terms respectively (not shown in the graph). For the Tecnis group there were statistically significant pre/post differences in the vertical astigmatism, vertical trefoil and tetrafoil (for 10.0 mm and 5.0 mm pupils) as well as other 6 and 10 higher-order terms, respectively (not shown in the graphs). In the Tecnis group, there were statistically significant preoperative and postoperative differences in vertical astigmatism, vertical trefoil, and tetrafoil (for 10.0 mm and 5.0 mm pupils) as well as other 8 and 6 higher-order terms (not shown in the graphs). There were not statistically significant differences in spherical aberration or coma-like terms. In terms of RMS, there were statistically significant differences in 3rd and higher-order terms, and 5th- and higher-order terms in the Acrysof IQ group and in 3rd and higher-order, 3rd order alone, 4th- and higher-order, 4th order alone, 5th- and higher-order and trefoil for the Tecnis group, both for 10 and 5-mm pupils. Spherical aberration and coma RMS did not change significantly in either group. Although the Techis group had a significant increase in more terms and orders than the Acrysof IQ group and the postoperative values in the Tecnis group were slightly higher, the differences between postoperative values across groups were not statistically significant.

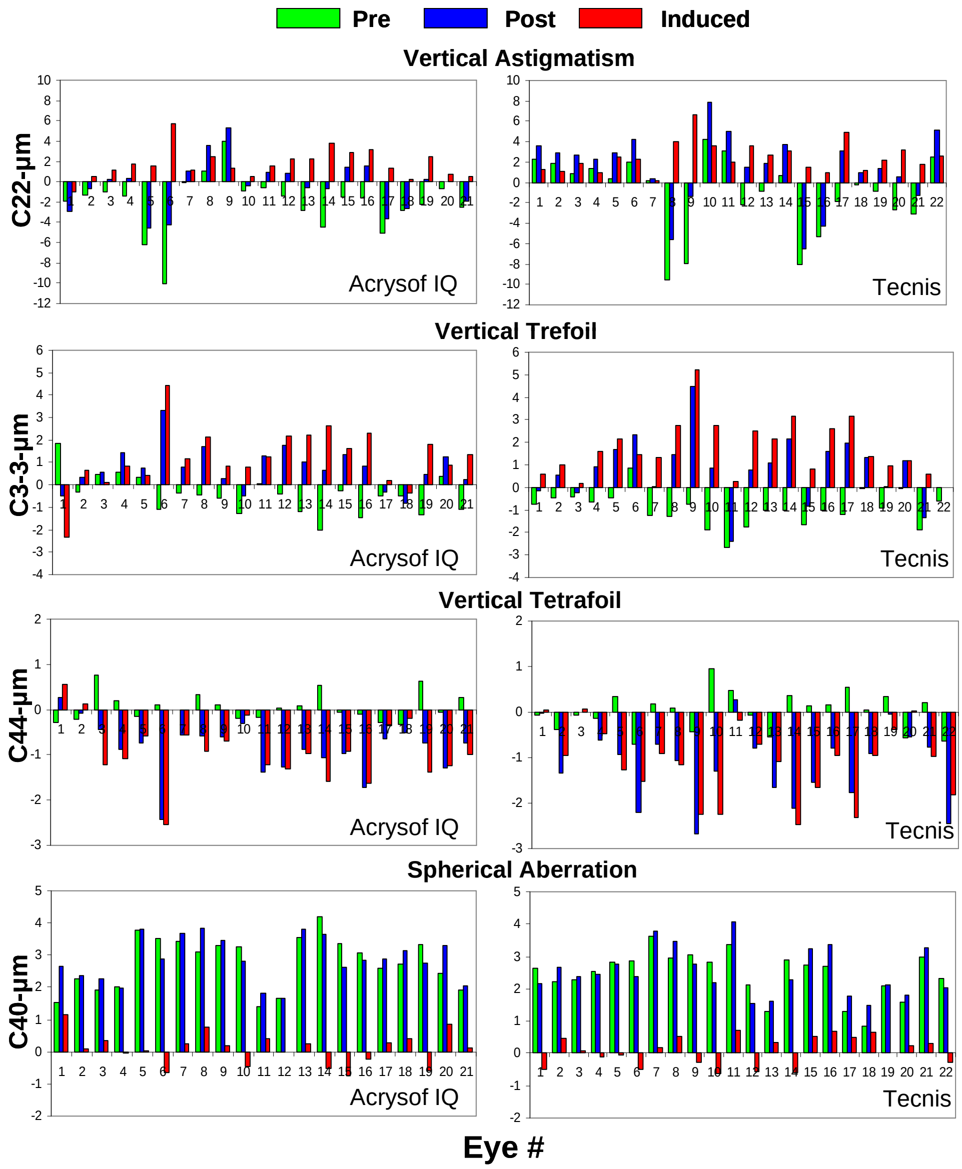

Figure 7.2. Preoperative, postoperative, and induced aberrations in all eyes of the study: 0/90 degree corneal astigmatic term, vertical trefoil,vertical tetrafoil and spherical aberration. Data are for a 10.0 mm corneal diameter.

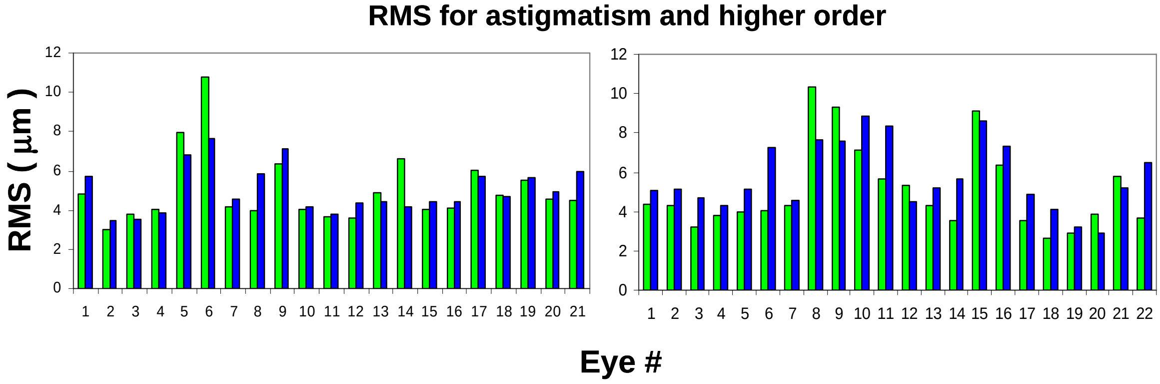

Figure 7.3. Preoperative and postoperative corneal RMS wavefront error in all eyes in the study. Data are for a 10.0 mm corneal diameter.

Table 7.2. Preoperative and postoperative RMS of the corneal wave aberration and relevant Zernike terms for the 2 groups of patients for 10.0 mm and 5.0 mm diameters. Statistical analysis corresponds to comparisons between groups (for preoperative and postoperative measurements) and between preoperative and postoperative measurements (in each group).

RMS/Zernike terms (μm)	Pre (10.0 mm)			Post (10.0 mm)			Differences pre/post *P*-value^{+} (10-mm)	
	Tecnis	Acrysof IQ	*P* -value§	Tecnis	Acrysof IQ	*P* -value§	Tecnis	Acrysof IQ
RMS all(no defocus or tilt)	5.06±2.10	5.01±1.78	0.93	5.75±1.72	5.01±1.19	0.11	0.0404*	0.98
RMS 3^{rd} & higher	3.54±0.66	3.83±0.53	0.12	4.31±1.17	4.29±0.68	0.95	0.0016*	0.004*
RMS 3rd	2.18±0.80	2.29±0.74	0.65	2.78±1.11	2.57±0.99	0.52	0.015*	0.20
RMS 4th	2.57±0.64	2.86±0.78	0.19	3.01±0.76	3.16±0.60	0.48	0.0006*	0.0095*
RMS 4^{th} & higher	2.69±0.62	2.95±0.75	0.23	3.22±0.80	3.31±0.59	0.66	0.0005*	0.0019*
RMS 5^{th} &higher	0.68±0.34	0.61±0.28	0.47	1.07±0.46	0.96±0.21	0.29	0.005*	<0.0001*
RMS Spherical	2.46±0.69	2.79±0.81	0.16	2.54±0.75	2.88±0.68	0.13	0.43	0.41
RMS trefoil	1.22±0.71	0.99±0.48	0.23	1.85±1.17	1.33±0.72	0.091	0.008*	0.080
RMS coma	1.68±0.75	1.95±0.87	0.28	1.82±0.93	2.10±0.95	0.338	0.43	0.46
Z22	-1.05±3.78	-2.07±2.79	0.32	1.42±3.52	-0.33±2.44	0.066	<0.0001*	<0.0001*
Z3-3	-0.95±0.76	-0.44±0.87	0.0456*	0.86±1.42	0.76±0.94	0.79	<0.0001*	0.0005*
Z40	2.45±0.70	2.78±0.81	0.16	2.53±0.74	2.87±0.68	0.12	0.45	0.42
Z44	0.01±0.43	0.06±0.31	0.66	-1.09±0.82	-0.83±0.58	0.25	<0.0001*	<0.0001*
RMS 3^{rd} & higher	0.29±0.12	0.27±0.06	0.35	0.46±0.18	0.43±0.11	0.53	0.003*	<0.0001*
RMS 3rd	0.24±0.12	0.21±0.07	0.37	0.40±0.19	0.36±0.13	0.44	0.006*	<0.0001*
RMS 4th	0.16±0.05	0.14±0.05	0.41	0.20±0.05	0.21±0.04	0.72	0.002*	0.0001*
RMS 4^{th} & higher	0.16±0.06	0.15±0.05	0.38	0.21±0.05	0.22±0.04	0.63	0.0007*	<0.0001*
RMS 5^{th} &higher	0.03±0.02	0.03±0.01	0.20	0.06±0.02	0.07±0.02	0.28	<0.0001*	<0.0001*
RMS Spherical	0.13±0.05	0.13±0.05	0.67	0.11±0.06	0.12±0.05	0.61	0.065	0.52
RMS trefoil	0.16±0.13	0.10±0.06	0.08	0.35±0.20	0.32±0.13	0.54	0.002*	<0.0001*
RMS coma	0.16±0.07	0.17±0.10	0.88	0.17±0.09	0.16±0.07	0.66	0.76	0.58
C22	-0.05±0.79	-0.36±0.56	0.13	0.57±0.67	0.26±0.62	0.12	<0.0001*	0.002*
C3-3	-0.09±0.15	-0.04±0.08	0.18	0.26±0.22	0.24±0.13	0.74	<0.0001*	<0.0001*
C40	0.13±0.05	0.13±0.05	0.66	0.11±0.06	0.12±0.05	0.57	0.067	0.52
C44	0.00±0.03	0.00±0.03	0.63	-0.12±0.07	-0.10±0.06	0.45	<0.0001*	<0.0001*

Z22, astigmatism at 0/90º; Z3-3, vertical trefoil; Z40, spherical 4^{th} order aberration; Z44 vertical tetrafoil

- p<0.05, significantly different with a confidence interval of 95%

§ unpaired t-test
\+ paired t-test

Despite the increase in certain aberrations, in general, corneal aberrations preoperatively correlated well with corneal aberrations post-operatively. In Acrysof IQ eyes, the correlation between all terms (except for tilt) preoperatively and postoperatively was positive and statistically significant in all eyes (*P*<0.0001). The mean slope across eyes was 0.91±0.21 (SD) and the correlation coefficient (*R*), 0.88±0.13. When defocus was excluded, the correlation was significant in all eyes except 2, and when defocus and astigmatism were excluded, the correlation was significant in all except 4 eyes. In Tecnis eyes, the correlation between all terms (except tilt) preoperatively and postoperatively was positive and statistically significant in all eyes except eyes 17, 18 and 20 ($P<0.0001$). The mean slope across eyes (excluding those 3 eyes) was 0.94±0.22 and R, 0.84±0.099. When defocus, astigmatism or both were excluded, the correlation was still significant in all except 5 eyes. Figure 7.4 shows the correlation between preoperative and postoperative Zernike coefficients in two typical eyes. The correlation was preserved primarily because spherical aberration and coma, major contributors to HOAs, do not change significantly with surgery. When analyzing correlations preoperatively and postoperatively (across all eyes), there was no correlation for 21 of the 35 Zernike coefficients for the Acrysof IQ group and 18 of 35 in the Tecnis group ($P>0.05$). Figure 7.5 shows the correlation between preoperative and postoperative for spherical aberration, vertical trefoil and vertical tetrafoil.

To average individual differences and find the typical changes in corneal aberrations induced by surgery, the mean induced wave aberration patterns were calculated. These are shown in Figure 7.6, and the corresponding coefficients are shown in Table 3, for 10.0 and 5.0 mm pupils. Table 3 shows the Zernike terms that were statistically significantly different from zero (primarily vertical astigmatism, trefoil and tetrafoil). Designers of computer eye models to test the effects of IOLs in optical performance can incorporate these induced aberrations in their models, adding them up to the preoperative corneal aberrations.

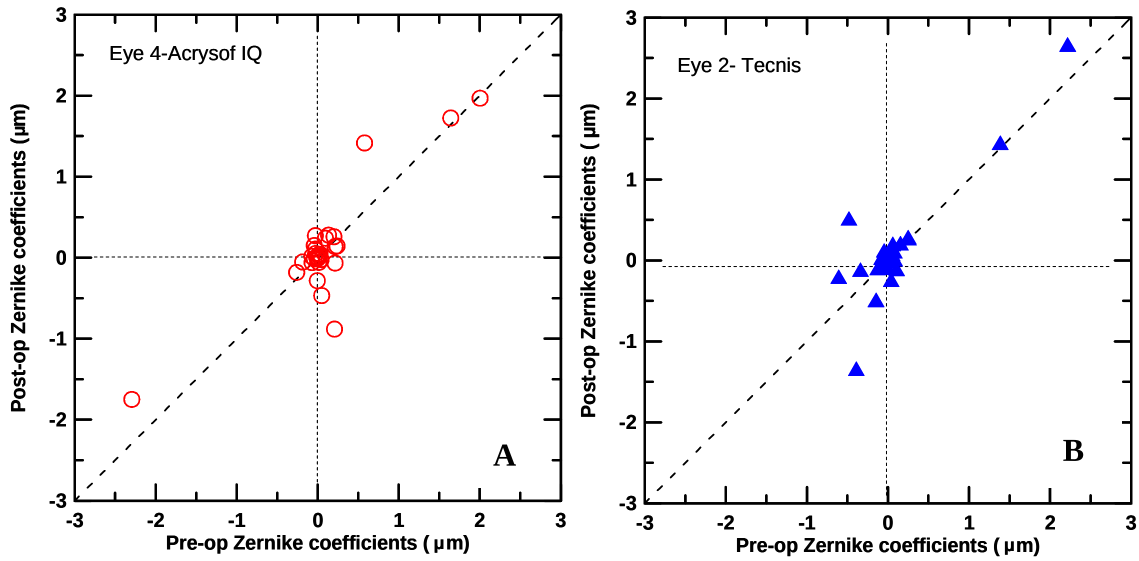

Figure 7.4. Correlation between preoperative and postoperative corneal Zernike coefficients (3 rd order and higher) in 2 eyes. **A**: Eye 4 with an Acrysof IQ IOL. **B**: Eye 2 with a Tecnis IOL. Slopes are 0.1 and 1.08, and correlation coefficients are 0.89 and 0.88 for (**A**) and (**B**), respectively. Dashed lines indicate y = x. Data are for a 10.0 mm corneal diameter.

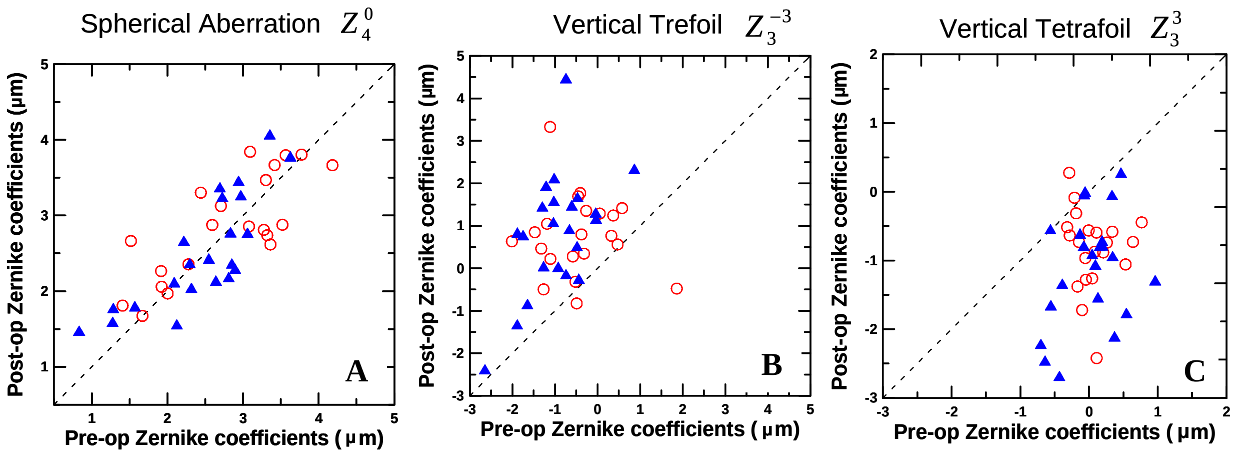

Figure 7.5. Correlations between preoperative and postoperative aberrations for all eyes. **A**: Corneal spherical aberration. **B**: Vertical trefoil. **C**: Vertical tetrafoil. Open circles represent eyes with the Acrysof IQ IOL and solid triangles, eyes with the Tecnis IOL. Dashed line corresponds to y = x. Data are for a 10.0 corneal diameter.

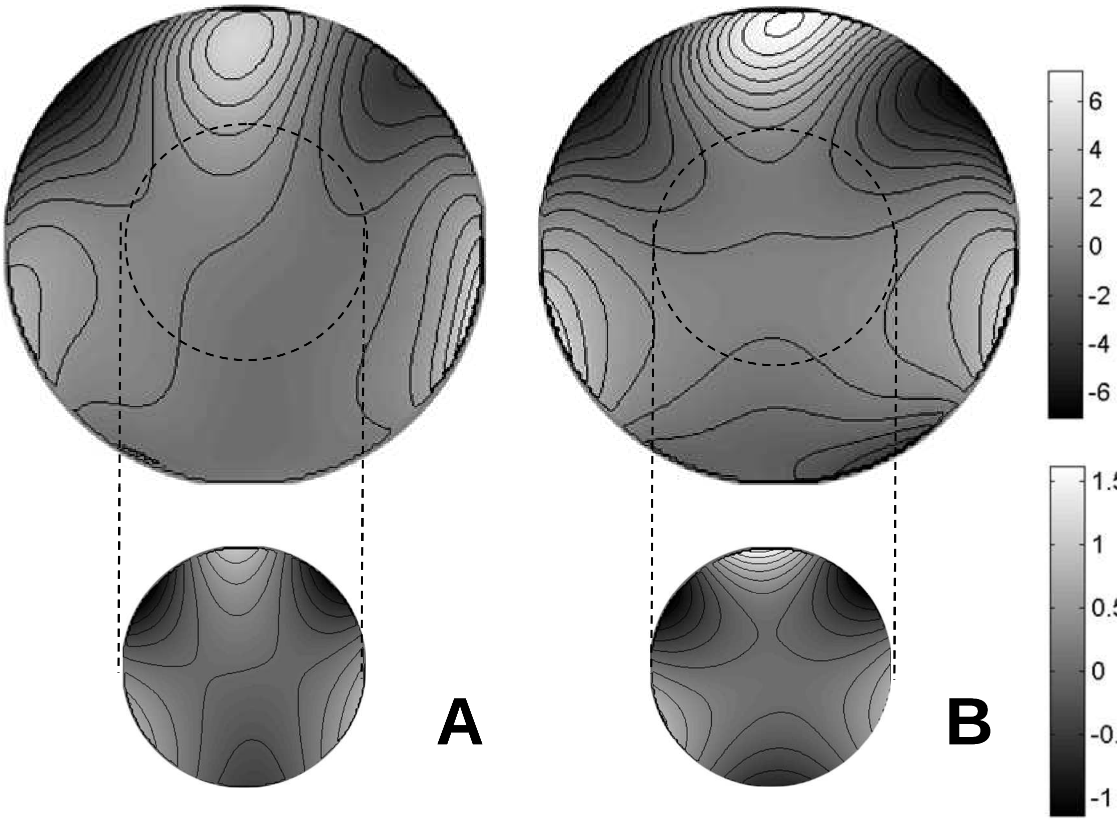

Figure 7.6. Mean induced corneal wave aberration maps for 3rd – and higher-order aberrations. **A**. Eyes with the AcrySof IQ IOL. **B**: Eyes with Tecnis IOL. Top maps are for 10.0 mm diameters, with contour lines every 1.00μm. Bottom maps are for 5.0 mm diameters, with contour lines every 0.25μm. Scale bars are different for each diameter. The 5.0 mm area is highlighted in the 10.0 mm map.

Table 7.3. Induced corneal aberrations (Zernike terms) in each group for 10.0 mm and 5.0 mm diameters and corresponding significance when comparing preoperative and postoperative terms.

	Tecnis (10-mm)		Tecnis (5-mm)		Acrysof (10 mm)		Acrysof (5 mm)	
Zernike coeff.	Average± std (μm)	P value	Average± std (μm)	P value	Average± std (μm)	P value	Average± std (μm)	P value
Z1_1	-0,73±2,25	0,143	-0,079±0,353	0,30	1,21±2,32	0,027*	0,228±0,297	0,002*
Z11	0,06±3,43	0,936	-0,024±0,268	0,68	-0,35±3,40	0,642	0,195±1,372	0,52
Z2_2	-0,12±1,11	0,609	0,035±0,218	0,45	0,00±0,75	0,9892	0,083±0,336	0,27
Z20	-0,11±1,06	0,641	0,019±0,060	0,15	0,11±1,11	0,656	0,003±0,043	0,78
Z22	2,47±1,50	p<0.0001*	0,623±0,390	p<0.0001*	1,74±1,44	p<0.0001*	0,618±0,257	p<0.0001*
Z3_3	1,81±1,19	p<0.0001*	0,344±0,240	p<0.0001*	1,20±1,34	0,0006*	0,277±0,125	p<0.0001*
Z3_1	-0,17±1,13	0,485	-0,036±0,109	0,13	0,37±1,24	0,190	0,068±0,089	0,002*
Z31	0,05±1,66	0,899	-0,003±0,103	0,87	-0,41±1,08	0,095	-0,023±0,083	0,23
Z33	-0,23±1,02	0,302	-0,084±0,174	0,034*	-0,07±0,86	0,696	-0,062±0,208	0,18
Z4_4	0,00±0,52	0,998	-0,054±0,071	0,0018*	-0,08±0,42	0,416	-0,028±0,109	0,26
Z4_2	-0,17±0,31	0,017*	0,004±0,026	0,49	-0,13±0,30	0,064	-0,005±0,030	0,44
Z40	0,07±0,45	0,448	-0,021±0,051	0,067	0,09±0,50	0,417	-0,005±0,034	0,51
Z42	-0,08±0,61	0,567	0,008±0,047	0,44	-0,24±0,65	0,103	-0,017±0,048	0,11
Z44	-1,10±0,79	p<0.0001*	-0,121±0,074	p<0.0001*	-0,89±0,68	p<0.0001*	-0,101±0,058	p<0.0001*
Z5_5	-0,19±0,49	0,092	-0,041±0,022	p<0.0001*	-0,24±0,26	0,0004*	-0,039±0,028	p<0.0001*
Z5_3	-0,20±0,41	0,036*	-0,011±0,020	0,014*	-0,18±0,38	0,049*	-0,014±0,016	0,0005*
Z5_1	0,12±0,39	0,169	-0,004±0,016	0,29	0,04±0,33	0,596	-0,006±0,015	0,07
Z51	-0,02±0,20	0,716	0,003±0,016	0,46	-0,06±0,16	0,104	-0,002±0,011	0,38
Z53	0,14±0,22	0,008*	0,003±0,013	0,33	0,09±0,23	0,077	0,005±0,016	0,18
Z55	-0,06±0,40	0,484	0,011±0,029	0,10	0,05±0,29	0,423	0,013±0,042	0,17
Z6_6	-0,06±0,36	0,472	-0,001±0,006	0,47	-0,01±0,22	0,877	0,000±0,003	0,88
Z6_4	0,19±0,21	0,0003*	0,003±0,003	0,0003*	0,08±0,32	0,252	0,001±0,005	0,25
Z6_2	-0,05±0,12	0,059	-0,001±0,002	0,059	-0,01±0,11	0,627	0,000±0,002	0,63
Z60	0,09±0,20	0,046*	0,001±0,003	0,045*	0,04±0,14	0,237	0,001±0,002	0,24
Z62	-0,05±0,22	0,347	-0,001±0,003	0,34	0,01±0,18	0,844	0,000±0,003	0,84
Z64	0,19±0,29	0,0063*	0,003±0,005	0,006*	0,16±0,17	0,0004*	0,003±0,003	0,0004*
Z66	0,13±0,37	0,118	0,002±0,006	0,12	0,11±0,25	0,051	0,002±0,004	0,051
Z7-7	-0,03±0,16	0,412	0,000±0,001	0,41	0,06±0,10	0,0146*	0,000±0,001	0,015*
Z7_5	0,21±0,13	p<0.0001*	0,002±0,001	p<0.0001*	0,20±0,17	p<0.0001*	0,002±0,001	p<0.0001*
Z7_3	0,03±0,12	0,255	0,000±0,001	0,25	0,05±0,09	0,0155*	0,000±0,001	0,015*
Z7_1	0,05±0,12	0,0815	0,000±0,001	0,08	0,05±0,10	0,043*	0,000±0,001	0,043*
Z71	-0,02±0,07	0,2421	0,000±0,001	0,24	0,00±0,08	0,885	0,000±0,001	0,89
Z73	0,01±0,09	0,599	0,000±0,001	0,5993	-0,01±0,08	0,536	0,000±0,001	0,54
Z75	-0,08±0,15	0,024*	-0,001±0,001	0,0244	-0,07±0,22	0,163	-0,001±0,002	0,16
Z77	0,01±0,17	0,745	0,000±0,001	0,745	0,02±0,15	0,487	0,000±0,001	0,49

4. DISCUSSION

We found that small-incision cataract surgery in patients implanted with two types of aspheric IOLs induced consistent and highly statistically significant changes in astigmatism and tetrafoil. The procedure did not induce significant changes in spherical aberration or coma terms. Interestingly, highly statistically significant differences were found not only in the largest area, but also for pupil diameters (5.0 mm) potentially relevant to vision.

Changes in corneal astigmatism are well known, and changes in corneal trefoil have also been reported. Our conclusions are stronger than those reported by Guirao (Guirao et al., 2004), likely because in our study, all eyes had superior incisions, which allows higher statistical power. While Guirao (Steinert & Deacon, 1996) do not report changes in tetrafoil term, we found that this term was consistently induced in all patients, with similar amounts (and opposite sign) than trefoil. In addition, along with vertical trefoil, it was responsible for the characteristic pattern of induced aberrations. To our knowledge, only Pesudovs (Pesudovs et al., 2005) have reported the presence of ocular tetrafoil in a group with spherical IOL implanted through a corneal incision (not with the same IOL implanted through a scleral incision). Because only total (and not corneal) aberrations were measured, they could not confirm the origin of this aberration. In addition, Guirao et al. used a different phakic group to perform the comparisons, whereas we compute the actual aberrations induced by performing measurements in the same eyes preoperatively and post- operatively.

We confirmed that neither spherical aberration nor coma changed significantly with the procedure. As a result, aspherical IOLs designed to compensate for the mean pre-operative corneal spherical aberration can work under the assumption that spherical aberration remains practically unchanged. Changes in astigmatism, trefoil and tetrafoil are not negligible and should be considered in simulations of optical outcomes of cataract surgery. Along with real corneal topographies and IOL design, corneal aberrations induced by the procedure should be considered when trying to predict the outcomes of cataract surgery, being potentially more important than the presence of moderate amounts of IOL tilt and decentration. The numerical data provided in Table 2 will help to produce more realistic predictions using eye models. Other potential changes, expected to be minor, refer to the posterior corneal surface.

We found slight differences in the change preoperative and postoperative aberrations with the two types of aspherical lenses, with the Tecnis IOLs showing a slightly higher increase in aberrations. Most differences between IOLs were not statistically significant and may not have visual consequences. Corneal diameters (particularly along the meridian of the incision) were not statistically different between groups; therefore, any difference in outcomes cannot be attributed to differences in the effective incision location (relative to the apex). In addition, we did not find a significant correlation between vertical corneal diameter and induced vertical astigmatism, trefoil and tetrafoil.

Although the study was designed to follow identical protocols in the two groups, and the incision size was purposely larger than the minimum values potentially allowed with the two injectors used to implant the two lens types (2.2 mm for the Acrysof HOA and 2.8 mm for the Tecnis), differences may be associated with slight final differences in incision size. The effective incision size after implantation was not measured. However, enlargement of incision at different steps of the procedure (Steinert & Deacon, 1996), and particularly differences between injectors have been reported before (Kohnen & Kasper, 2005), and may play some role in the observed tendencies.