ABSTRACT

PURPOSE: To compare visual acuity, total and high order wavefront aberrations (coma, spherical aberration, and other terms of high order aberration), and contrast sensitivity in 105 eyes implanted with 4 different types of intraocular lenses (IOLs) (1 multifocal apodized diffractive IOL and 3 monofocal IOLs).

METHODS: A prospective study comparing four types of IOLs (Alcon ReSTOR [50 eyes], Alcon Acrysof MA30AC [20 eyes], Alcon Acrysof SA60AT [20 eyes], and Mediphacos Acqua IOL [15 eyes]) was carried out. All eyes were targeted for emmetropia. Complete ophthalmological examination, including uncorrected visual acuity (UCVA), best spectacle-corrected visual acuity (BSCVA), contrast sensitivity (Pelli-Robson chart), and wavefront analysis, was performed 2 months postoperatively.

RESULTS: All eyes in all groups had BSCVA 20/32 postoperatively. Mean total aberration root-mean-square (RMS) values were: 0.72±0.25 µm (ReSTOR), 0.94±0.26 µm (MA30), 0.84±0.23 µm (SA60), and 2.04±0.77 µm (Acqua). Mean higher order aberration values were: 0.35±0.15 µm (ReSTOR), 0.41±0.12 µm (MA30), 0.43±0.13 µm (SA60), and 0.85±0.50 µm (Acqua). The Acqua IOL showed statistically significant more total and higher order aberrations when compared to the other IOLs (P<.05). The ReSTOR IOL showed statistically significant less induction of spherical aberration when compared to the monofocal IOLs (P<.05). Mean contrast sensitivity values were: 1.64±0.08 (ReSTOR), 1.72±0.08 (MA30), 1.70±0.07 (SA60), and 1.65±0.11 (Acqua).

CONCLUSIONS: Different types of IOLs resulted in measurably different postoperative higher order aberration patterns. The multifocal apodized diffractive IOL (ReSTOR) induced significantly less spherical aberration compared to the monofocal IOLs. Contrast sensitivity revealed better values with MA30 and SA60 IOLs when compared to ReSTOR. The integration of wavefront technology in evaluating pseudophakic patients represents a step towards better understanding and analyzing postoperative visual quality. [J Refract Surg. 2005;21: S808-S812.]

Cataract surgery and intraocular lens (IOL) implantation is becoming more of a refractive procedure, where results are not only measured by means of visual acuity, but also by quality of vision.

Contrast sensitivity and wavefront analysis effectively represent the optical quality of vision. With wavefront technology, the aberrations (low and high order aberrations) present in an optical system can be measured. High order optical aberrations, such as spherical aberration and coma, have an impact on contrast sensitivity and functional vision. Highly aberrated eyes have a poor contrast and poor quality of vision that cannot be corrected with eyeglasses or contact lenses.1-3

The IOL materials and designs have been extensively improved to provide the best quality of vision after cataract removal. Some IOLs are designed to compensate for the spherical aberration of the cornea, which in turn would improve contrast sensitivity at low and mid spatial frequencies.4,5

Recently, new IOLs have been developed to lessen patient’s spectacle dependence, such as diffractive multifocal and pseudoaccommodative IOLs, but the optical performance by means of wavefront analysis and contrast sensitivity of these IOLs has not yet been described.

This prospective study aims to compare visual acuity, total and high order wavefront aberrations (coma, spherical aberration and other terms of higher order aberrations), and contrast sensitivity in 105 eyes implanted with 4 different IOL types (1 multifocal apodized diffractive IOL and 3 monofocal IOLs).

PATIENTS AND METHODS

A prospective study comparing four types of IOLs—Alcon ReSTOR (50 eyes), Acrysof MA30AC (20 eyes), Acrysof SA60AT (20 eyes) (Alcon Laboratories Inc, Ft Worth, Tex), and Mediphacos Acqua (15 eyes) (Mediphacos, Belo Horizonte, Brazil)—was carried out at the Federal University of Sao Paulo, Brazil. Patients who underwent clear corneal phacoemulsification and IOL implantation were followed prospectively.
from February to September 2004. Inclusion criteria were corneal astigmatism < 1 diopter, no ocular-associated diseases, and potential acuity meter > 0.2 logMAR units. Patients with ocular disease, such as dry eye, corneal opacities, glaucoma, retinal abnormalities, surgical complications, or IOL tilt, were excluded.

All surgeries were performed by two experienced surgeons (E.S.S., L.L.F.). The eyes were selected to receive different IOL types. Surgeon E.S.S. performed 65 surgeries (including all ReSTOR cases and 5 cases of each remaining IOL) and surgeon L.L.F. performed 40 surgeries (15 MA30 cases, 15 SA60 cases, and 10 Acqua cases). Continuous curvilinear capsulorrhexis with an approximate 5.0-mm diameter was created. The IOLs were implanted in the capsular bag.

Patients were examined 1, 7, 15, and 30 days after surgery, and the final follow-up examination was at 2 months postoperatively. At that time, complete ophthalmological examination including uncorrected visual acuity (UCVA), best spectacle-corrected visual acuity (BSCVA) (ETDRS chart), microscopy, applanation tonometry, fundus examination, contrast sensitivity (Pelli-Robson chart; Clement Clarke International, London, UK), and wavefront analysis with the LADARWave aberrometer (Alcon Laboratories) were performed. The Pelli-Robson contrast sensitivity test was performed using a 1-m distance (corresponding to a spatial frequency of approximately 1 cycle per degree) and a luminance of approximately 85 cd/m² (Goslen-Starlite). Absolute values of log contrast sensitivity were obtained for each eye. The wavefront maps were analyzed using a 5-mm pupil diameter and up to the 6th order of Zernike coefficients.

Statistical analysis was performed using Kruskal-Wallis test and analysis of variance test; \( P < 0.05 \) was considered statistically significant. The Kruskal-Wallis tests were followed with the Dunn pairwise multiple comparisons among the four groups to identify which groups were significantly different.

**RESULTS**

Sixty-seven patients (35 men [52%] and 32 women [48%]) (105 eyes) were enrolled in this study. Average patient age was 62.25 years (range: 50 to 77 years). Mean patient age in each group was: 64 years, ReSTOR; 61 years, MA30; 60 years, MA30; 61 years, SA60; and 64 years, Acqua.

All eyes in all groups had BSCVA of \( \geq 20/25 \) postoperatively. Best spectacle-corrected visual acuity was \( \geq 20/25 \) in 90% of eyes in the ReSTOR group, 85% of eyes in the MA30 group, 100% of eyes in the SA60 group, and 85% of eyes in the Acqua group (Table 1).

The induced astigmatism was not statistically significant \( (P > 0.05) \). No significant differences were noted between the groups in age, corneal curvature, axial length, IOL power, or mean follow-up. The IOL centration was not measured by any specific method, but was observed under slit-lamp examination.

Postoperative wavefront analysis revealed mean total aberration root-mean-square (RMS) values of \( 0.72 \pm 0.25 \) \( \mu m \) (ReSTOR), \( 0.94 \pm 0.26 \) \( \mu m \) (MA30), \( 0.84 \pm 0.23 \) \( \mu m \) (SA60), and \( 2.04 \pm 0.77 \) \( \mu m \) (Acqua). Mean higher order aberration values were \( 0.35 \pm 0.15 \) \( \mu m \) (ReSTOR), \( 0.41 \pm 0.12 \) \( \mu m \) (MA30), \( 0.43 \pm 0.13 \) \( \mu m \) (SA60), and \( 0.85 \pm 0.50 \) \( \mu m \) (Acqua) (Table 2). No statistically significant difference was found between MA30, SA60, and ReSTOR IOLs when looking at total and higher order aberration RMS values; however, these three IOLs showed significantly less total and higher order aberration values when compared to the Acqua group \( (P < 0.001) \).

The ReSTOR, MA30, and SA60 IOLs showed statistically significant less defocus \( (P < 0.001) \) and astigmatism \( (P = 0.048) \) measured with the wavefront sensor than the Acqua IOL (Table 3).

When analyzing each higher order aberration separately, coma values were \( 0.13 \pm 0.09 \mu m \) (ReSTOR), \( 0.17 \pm 0.08 \mu m \) (MA30), \( 0.15 \pm 0.07 \mu m \) (SA60), and \( 0.23 \pm 0.11 \mu m \) (Acqua), and the difference between the ReSTOR and Acqua group was statistically significant \( (P = 0.012) \), with the ReSTOR IOL inducing less coma-like aberrations (Table 3).

The ReSTOR IOL obtained statistically significant less spherical aberration when compared to all of the monofocal IOLs tested (ReSTOR \( 0.09 \pm 0.05 \mu m \); MA30 \( 0.23 \pm 0.08 \mu m \); SA60 \( 0.25 \pm 0.08 \mu m \) \( P < 0.001 \)), whereas the Acqua IOL showed the highest values \( 0.37 \pm 0.04 \mu m \) \( P < 0.001 \) (Table 3).

Mean contrast sensitivity values, measured by Pelli-Robson test, were \( 1.64 \pm 0.08 \) (ReSTOR), \( 1.72 \pm 0.08 \) (MA30), \( 1.70 \pm 0.07 \) (SA60), and \( 1.65 \pm 0.11 \) (Acqua).
The MA30 and SA60 IOL groups were not statistically significantly different, whereas the ReSTOR group presented the worst contrast sensitivity values ($P=.002$) (Table 4).

**DISCUSSION**

Studies demonstrated that during life the crystalline lens compensates for the cornea positive spherical aberration, compensating for the total aberration of the eye. The aging lens changes its balance with the cornea, with a reduction in the negative spherical aberration of the crystalline lens.1,7-10 Intraocular lens implantation increases spherical aberration and wavefront variances, as conventional monofocal IOLs are either plane-convex or biconvex and they can only introduce positive spherical aberration.11,12 Some pseudophakic patients complain about glare, halos, and starburst that could be attributed to spherical aberration.11,13 The IOL decentration and tilt creates an asymmetrical high order aberration, related to coma and secondary astigmatism.2

Wavefront technology was first described to evaluate low and high order aberrations in normal, phakic eyes. However, this technology can also be used to measure pseudophakic eyes.14,15 When the pupil diameter analyzed is smaller than the IOL optical zone, the Hartmann-Shack spot patterns can be appropriately measured and analyzed.

The multifocal IOL (ReSTOR), with an apodized diffractive surface based on the Huygens-Fresnel principle, induced statistically significant less spherical aberration when compared to the monofocal IOLs (ReSTOR 0.09±0.05 µm; MA30 0.23±0.08 µm; SA60 0.25±0.08 µm; Acqua 0.37±0.04 µm) ($P<.05$). The apodized diffractive surface behaved as an aspherical surface, showing less spherical aberration. The ReSTOR showed lower mean total aberration RMS values (ReSTOR, 0.72±0.25 µm; MA30, 0.94±0.26 µm; SA60, 0.84±0.23 µm; Acqua, 2.04±0.77 µm) and lower mean high order aberration values (ReSTOR, 0.35±0.15 µm; MA30, 0.41±0.12 µm; SA60, 0.43±0.13 µm; and Acqua, 0.85±0.50 µm). No statistically significant difference was found between MA30 and SA60 IOLs.

It has been demonstrated that the Tecnis Z9000 IOL (Advanced Medical Optics, Santa Ana, Calif), with a modified prolate anterior surface design, induced less spherical aberration.1-5,12 Bellucci et al3 compared five types of IOLs—the Tecnis Z9000 showed lower spherical aberration, although no difference was found in coma, and little difference was found in high order aberration between the other IOLs (Acrysof SA60AT and MA60BN [Alcon Laboratories], Sensar AR40e, and CeeOn 911Edge [AMO, Santa Ana, Calif]). Taketani et al16 found no significant differences between a hydrophilic acrylic IOL (Hydroview) and a hydrophobic acrylic IOL (Acrysof MA30BA [Alcon Laboratories]) in coma or total high order aberration; however, the Acrysof IOL induced higher spherical aberration (0.696±0.287 vs 0.441±0.147) at a 6-mm pupil diameter.

The use of contrast sensitivity tests with letters as optotypes, such as the Pelli-Robson test, is reliable, repeatable and easy to apply.16-19 In our study including pseudophakic patients, the implanted ReSTOR IOL and Mediphacos Acqua IOL showed worse mean contrast sensitivity values (ReSTOR, 1.64±0.08; Acqua, 1.65±0.11; MA30 1.72±0.08; and SA60 1.70±0.07). Mäntyjärvi and Laitinen6 studied normal values for the Pelli-Robson test at a 1-m distance in a group of subjects.

<table>
<thead>
<tr>
<th>Total RMS</th>
<th>ReSTOR (n=50)</th>
<th>MA30 (n=20)</th>
<th>SA60 (n=20)</th>
<th>Acqua (n=15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean±SD</td>
<td>0.72±0.25</td>
<td>0.94±0.26</td>
<td>0.84±0.23</td>
<td>2.04±0.77</td>
</tr>
<tr>
<td>Median</td>
<td>0.70</td>
<td>0.92</td>
<td>0.87</td>
<td>1.74</td>
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<tr>
<td>Min - Max</td>
<td>0.25 - 1.32</td>
<td>0.40 - 1.31</td>
<td>0.41 - 1.22</td>
<td>1.20 - 3.30</td>
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</tbody>
</table>

Kruskal-Wallis test  $P<.001^*$

<table>
<thead>
<tr>
<th>Higher order aberration RMS</th>
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</thead>
<tbody>
<tr>
<td>Mean±SD</td>
</tr>
<tr>
<td>0.35±0.15</td>
</tr>
<tr>
<td>0.41±0.12</td>
</tr>
<tr>
<td>0.43±0.12</td>
</tr>
<tr>
<td>0.85±0.50</td>
</tr>
</tbody>
</table>

Kruskal-Wallis test  $P<.001^*$
patients aged 60 to 75 years, showing a mean value of 1.72±0.08. Rubin et al. studied contrast sensitivity in multifocal IOL implants and found similar results when compared to our study (1.65±0.08). Elliott and Whitaker21 published normal values for the Pelli-Robson test in phakic individuals in different age groups and found worse contrast than what we report (1.50 for individuals aged >50 years). It is also important to point out that Montés-Micó and Alió17 observed an increase in contrast sensitivity over time in patients with multifocal IOLs, suggesting adaptation of the patient over time that could, in turn, improve the contrast sensitivity measurement if performed after 6 months of implantation. This could be why, despite having less aberrations, the ReSTOR group did not show a better contrast sensitivity performance when compared to the other IOL groups. Longer follow-up with contrast sensitivity re-test will be necessary to clarify this.

With the advent of wavefront technology, it has been possible to quantify total ocular aberrations and to better understand the potential benefits of a customized IOL to correct the aberrations of the cornea. The compensation for the corneal aberrations should enhance visual performance by greatly improving retinal image quality and optimizing surgical results. By this means, using one IOL type that induces less aberrations could potentially improve visual quality.

The multifocal apodized diffractive IOL (ReSTOR) induced significantly less spherical aberration than all other monofocal IOLs. The integration of wavefront technology, it has been possible to quantify total ocular aberrations and to better understand the potential benefits of a customized IOL to correct the aberrations of the cornea. The compensation for the corneal aberrations should enhance visual performance by greatly improving retinal image quality and optimizing surgical results. By this means, using one IOL type that induces less aberrations could potentially improve visual quality.
Wavefront Analysis of ReSTOR/Rocha et al

TABLE 4
Postoperative Contrast Sensitivity Measured With Pelli-Robson Chart for All IOL Types

<table>
<thead>
<tr>
<th>Contrast Sensitivity</th>
<th>ReSTOR (n=50)</th>
<th>MA30 (n=20)</th>
<th>SA60 (n=20)</th>
<th>Acqua (n=15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
<td>7 (14)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>4 (26.7)</td>
</tr>
<tr>
<td>1.65</td>
<td>39 (78)</td>
<td>11 (55)</td>
<td>13 (65)</td>
<td>7 (46.7)</td>
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<tr>
<td>1.80</td>
<td>3 (6)</td>
<td>9 (45)</td>
<td>7 (35)</td>
<td>4 (26.7)</td>
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<td>1.95</td>
<td>1 (2)</td>
<td>0 (0)</td>
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</tr>
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</table>

Kruskal-Wallis test $P = .002^*$

REFERENCES