ARTICLE

Disk halo size measured in individuals implanted with monofocal versus diffractive multifocal intraocular lenses

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PURPOSE: To compare disk halo size in response to a glare source in eyes implanted with an aspheric apodized diffractive multifocal intraocular lens (IOL) or aspheric monofocal IOL.

SETTING: Rementeria Ophthalmological Clinic, Madrid, Spain.

DESIGN: Prospective randomized masked study.

METHOD: Halo radius was measured using a vision monitor (MonCv3) with low-luminance optotypes in 39 eyes that had cataract surgery and the bilateral implant of an Acrysof Restor SN6AD1 multifocal IOL or Acrysof IQ monofocal IOL 6 to 9 months previously. The visual angle subtended by the disk halo radius was calculated in minutes of arc (arcmin). Patient complaints of halo disturbances were recorded. Monocular uncorrected distance visual acuity (UDVA) and corrected distance visual acuity (CDVA) were measured using high-contrast (96%) and low-contrast (10%) logMAR letter charts.

RESULTS: The study comprised 39 eyes of 39 subjects (aged 70 to 80 years); 21 eyes had a multifocal IOL and 18 eyes a monofocal IOL. Mean halo radius was 35 arcmin larger in the multifocal IOL group than the monofocal group ($P < .05$). Greater halo effects ($P < .05$) were reported in the multifocal IOL group. Mean monocular high-contrast UDVA and low-contrast UDVA did not vary significantly between groups, whereas mean monocular high-contrast CDVA and low-contrast CDVA were significantly worse at 0.12 and 0.13 logMAR ($P < .01$) in the multifocal than in the monofocal IOL group, respectively. A significant positive correlation ($r = 0.72$, $P < .001$) was detected by multiple linear regression between the halo radius and low-contrast UDVA in the multifocal IOL group.

CONCLUSIONS: The diffractive multifocal IOL gave rise to a larger disk halo size, which was correlated with a worse low-contrast UDVA.

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Current diffractive multifocal intraocular lenses (IOLs) provide satisfactory distance, intermediate, and near visual acuity, reducing spectacle dependency.[1] However, adverse subjective visual phenomena, such as glare and halos, are often reported by patients with multifocal IOLs, especially when driving at night.[1] Theoretical optical design predictions suggest that multifocal IOLs will induce more light scatter than monofocal IOLs.[2] In a refractive–diffraction IOL designed to simultaneously yield focused images of near and far objects,[3] forward scattered light from a glare source forms a veil of luminance over the retina.

Disk halos form because the out-of-focus image has a larger diameter than the sharp image on the retina.[4] The unwanted effect of the light in the out-of-focus image may be visually disturbing, depending on 2 factors: the distance along the optical axis between these 2 images (the greater the distance between the 2 separate focal points along the optical axis, the greater will be the diffusion or blur circle surrounding the primary focus), and their relative energy distribution (the energy of the distant and near images is a function of pupil size).[5] As a consequence, contrast sensitivity and undesirable optical effects such as glare

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and/or halos may be worse in eyes implanted with a multifocal rather than a monofocal IOL.[6–8]

Although disability glare or straylight determined using the C-Quant related to the implant of diffractive multifocals have been fairly well established, halos induced by a glare source have been scarcely addressed in this setting. Diffractive multifocals have been described to produce higher straylight values than monofocal IOLs,[9–11] yet some authors have reported no such differences.[12,13] The varied findings among studies may be attributed to the different IOL types analyzed and other methodological aspects. No differences in straylight have been detected for spherical compared to aspheric IOLs.[14,15] In a study in which subject age was taken into account, multiple linear regression analysis using log straylight as the dependent variable revealed that both age and IOL type had an effect on the amount of straylight generated.[11] Few studies have centered on obtaining objective halo size measurements in subjects implanted with an intraocular lens.[4,16] Dick et al.[16] detected a significantly greater mean halo size in subjects older than 70 years with zonal-progressive multifocal IOLs compared to monofocals.[16] Refractive multifocal IOLs were also found to give rise to a significantly greater halo size than monofocals.[4] Halometry has been used to measure the angular size of photopic scotomas arising from a glare source in subjects with diffractive trifocal IOLs.[17] To the best of our knowledge, however, no study has compared examined halo size measurements related to the use of diffractive multifocal and monofocal IOLs.

This study was designed to determine the size of a disk halo induced by a glare source positioned at far in a carefully selected sample of eyes implanted with a diffractive multifocal IOL with +3.00 diopters (D) of addition power or an aspheric monofocal IOL. Correlations between halo size and high-contrast visual acuity and low-contrast visual acuity were also determined.

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PATIENTS AND METHODS

Patients

For this comparative study, healthy individuals who, 6 to 9 months previously, had had cataract surgery with the bilateral implant of an aspheric apodized diffractive multifocal Acryzof Restor SN6AD1 IOL (multifocal IOL group) or an aspheric monofocal AcrySof IQ SN60WF IOL (monofocal IOL group) were recruited from the database of Rementeria Ophthalmological Clinic, Madrid, Spain (both IOLs Alcon Laboratories, Inc.). Subjects were required to be in the age range of 70 to 80 years to avoid the need to correct for the known effect of age on halo measurements.[18] The study protocol adhered to the tenets of the Declaration of Helsinki and received approval from the review board of the San Carlos University Hospital Madrid (ref. no. 12/429-E). All participants signed an informed consent form.

Exclusion criteria were a history of previous ocular surgery (other than cataract), corneal scars or haze, vitreous floaters, ophthalmic diseases (e.g. glaucoma, retinopathy), systemic disease (e.g. diabetes), any postoperative complications of cataract surgery (eg, any sign of posterior capsule opacification) and a postoperative best-corrected distance visual acuity (CDVA) worse than 20/25.

All eyes were subjected to a thorough ophthalmologic examination including visual acuity, subjective refraction, axial length, slitlamp biomicroscopy, and ophthalmoscopy. The examiner was blinded to the subject group. Measurements were made in one randomly selected eye of each patient.

Intraocular Lenses

The Acrysof Restor SN6AD1 and Acrysof IQ SN60WF IOLs feature the same hydrophobic acrylic material with a blue light–filtering chromophore and the same aspheric design to compensate for the natural positive spherical aberration of human corneas.[19] Acrysof Restor SN6AD1 is an apodized hybrid IOL combining diffractive and refractive regions with +3.00 D of addition. The diffractive region covers the central 3.6 mm of the lens and is formed by 9 concentric steps of gradually decreasing height that divert light simultaneously to distance and near foci. The outer region of the lens is purely refractive and sends light only to the distance focus.

Surgical Technique

All cataract surgeries were performed by the same surgeon. All patients underwent a 2-mm clear corneal incision, continuous curvilinear capsulorhexis, and phacoemulsification (Constellation Vision System, Alcon Laboratories, Inc.) followed by irrigation and aspiration of the cortex and IOL implantation in the capsular bag. Postoperatively, the pupils in all eyes were round without iris trauma.

Visual Acuity

Monocular uncorrected distance visual acuity (UDVA) was measured using high-contrast (96%) and low-contrast (10%) Bailey-Lovie logMAR letter charts at a distance of 4 m. Subjects were encouraged to guess letters even if they were unsure, although testing was stopped when 4 mistakes in a row were made. Each letter read correctly on each line was given a score of 0.02 log units. Thus, scoring was letter by letter. In these charts, a loss of one line of letters corresponds to a logMAR increase of 0.1.

Halo Size Measurements

Halo size was measured using a vision monitor (MonCv3, Metrovision, France). This halo measurement is a clinical psychophysical test. The method has been described in detail elsewhere.[18] The vision monitor has 2 white sources on each side to generate glare. Each glare source has 7 light-emitting diodes (each 5 mm in diameter) in a circular area of 213.8 mm^2, has a single luminance of 200,000 candelas/m^2, and forms a visual angle of 3.8 degrees from the center of the monitor at a distance of 2.5 m. The right source was chosen to test right eyes and the left source to test left eyes. The light source illuminates the patient's eye and produces stray intraocular light, reducing the contrast of a foveal target. In this study, the test was performed using a letter luminance level of 5 cd/m^2. Optotypes on the monitor screen are arranged in 3 radial lines of letters emerging from the periphery toward the glare source. Each line contains 10 letters forming 10 rings at intervals of 33 arcmin at a distance of 2.5 m. Each letter subtends an angle of 15 arcmin corresponding to a visual acuity of 20/60 (0.48 logMAR).

Before testing, the subject was allowed to dark adapt for 5 minutes, and pupil size was measured using a Colvard pupillometer. Monocular testing with the best spectacle correction took place in a dark room. The subject was seated 2.5 m from the screen with the head aligned, using a chinrest, with the center of the screen. The subject was instructed to look at the instrument but on the opposite side of the glare source to avoid looking directly at the light to avoid a retinal afterimage that could prevent recognition of the letters. Thereafter, the optotypes were read from the periphery toward the glare source until a letter could not be identified. The subject was encouraged to read each letter despite being unsure. Letters not identified in each line were recorded, and the test result was calculated as the average distance from the glare source for the 3 lines. This distance was recorded as the radius of the halo. Next, the visual angle formed by the radius of the halo was calculated in arcmin.

Finally, subjects rated the halos perceived in daily life situations using the following scale: 1 = none, 2 = mild, 3 = moderate, and 4 = severe, as described by others.[20]

Statistical Analysis

Statistical analysis was performed using the Statgraphics Centurion Version XVI program. According to prior power calculations, for a critical *P* value of 0.05 the minimum sample size was 18 subjects per IOL group. This would be sufficient to detect statistical significance for an anticipated mean halo radius difference greater than 33 arcmin between the groups. The calculation assumed an overall variability of 33 arcmin and a power of 0.90. In the multifocal IOL group, we were able to recruit 3 additional subjects and decided to enter them in the study. The normal distribution of the halo radius and visual acuity variables in each IOL group was confirmed using the Shapiro-Wilk *W* test.

The Student *t* test for unpaired data was used to compare halo size, self-reported halos, and visual acuity outcomes between the monofocal and multifocal IOL groups. Halo radius and self-perceived halo were correlated using Spearman rank correlation coefficients. Multiple linear regression analysis was used to determine the relative contribution of visual acuity variables explaining variance in halo size. Significance was set at a *P* value of less than 0.05.

RESULTS

The study comprised 39 eyes of 39 subjects (aged 70 to 80 years); 21 eyes had a multifocal IOL and 18 eyes a monofocal IOL. The demographic and baseline characteristics of the subjects in the multifocal and monofocal IOL groups are provided in Table 1. Groups were well-matched in terms of age, sex, axial length, pupil size, pre- and postoperative visual acuity and pre- and postoperative sphere and/or cylinder ($P > .05$).

Figure 1 shows box plots of halo radius (arcminutes) for the monofocal and multifocal IOL groups. Mean (±SD) halo radii were 190.06 ± 56.70 arcmin (range 99 to 286 arcmin or 1.65 to 4.76 degrees) and 225.24 ± 39.91 arcmin (range 165 to 297 arcmin or 2.75 to

Table 1. Demographic and baseline characteristics of the study participants.

Characteristic	Monofocal IOL	Multifocal IOL	*P*
No. of eyes	18	21	
Age, y	74.1 ± 2.1 (70.0, 78.0)	73.8 ± 2.5 (70.0, 78.0)	.643
Sex, male/female	6/11	5/16	.258
Axial length, mm	23.68 ± 1.32 (21.73, 26.16)	23.28 ± 0.50 (22.23, 24.25)	.198
Mesopic pupil size, mm	4.24 ± 0.77 (3.00, 6.00)	4.24 ± 0.70 (2.00, 5.00)	.991
Preop visual acuity (Snellen)	20/27 (20/125, 20/20)	20/28 (20/100, 20/20)	.729
Postop visual acuity, Snellen	20/20 (20/20, 20/18)	20/20 (20/25, 20/17)	.346
Preop sphere, D	0.54 ± 2.81 (–4.25, 8.00)	1.57 ± 1.98 (–1.50, 5.50)	.199
Preop cylinder, D	−0.71 ± 0.83 (–3.00, 0.00)	−0.68 ± 0.68 (−2.50, 0.00)	.912
Postop sphere, D	0.00 ± 0.24 (–0.50, +0.75)	0.10 ± 0.20 (0.00, 0.75)	.186
Postop cylinder, D	−0.22 ± 0.32 (–0.75, 0.00)	−0.29 ± 0.36 (–1.00, 0.00)	.560

IOL = intraocular lens; Postop = postoperative; preop = preoperative
Data are mean ± SD (minimum, maximum)

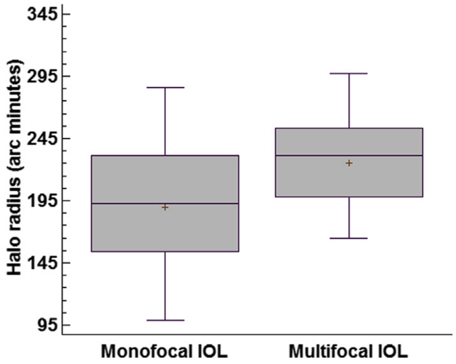

Figure 1. Box plots of halo radius (arcmin) values recorded in the monofocal and multifocal intraocular lens (IOL) groups.

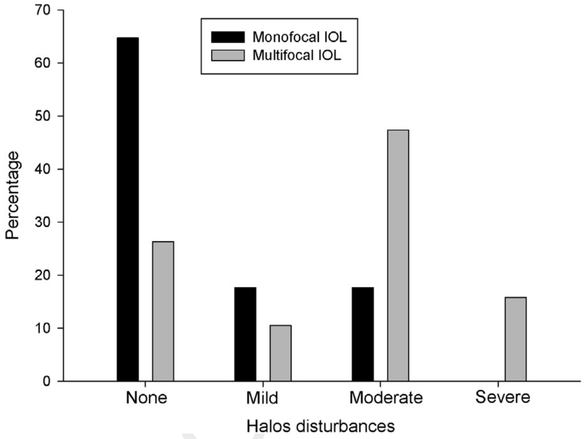

Figure 2. Halos self-reported in the monofocal and multifocal intraocular lens (IOL) groups.

4.95 degrees) in the monofocal and multifocal IOL groups, respectively. The last 3 letters along each radius (furthest from the glare source) were seen by all subjects. Mean halo radius was 35 arcmin (aproximatly one ring of the test) larger in the multifocal group than in the monofocal IOL group ($t = -2.265$; $P = .0294$).

Subject complaints of halos following IOL implant were quantified using a self-perceived halo rating scale. A greater proportion of subjects rated halos as moderate to severe in the multifocal IOL group (63.2%) than in the monofocal IOL group (17.6%) ($\chi^2 = 8.365$, $P = .0390$) (Figure 2). Mean halo ratings were 1.5 ± 0.8 (SD) and 2.5 ± 1.07 in the monofocal and multifocal IOL groups, respectively ($t = -3.129$; $P = .00359$). No significant correlation was detected between disk halo size and self-reported halos (Spearman rank correlation coefficients −0.09 to −0.20).

Table 2 provides the mean values of distance high-contrast and low-contrast visual acuity (logMAR) recorded without and with best spectacle correction in the monofocal and multifocal IOL groups. Mean best spectacle corrections were −0.12 ± 0.31 D (SD) and −0.08 ± 0.29 D of spherical equivalent in the monofocal and multifocal IOL groups, respectively. Although a trend toward better postoperative UDVA was observed in the monofocal IOL group, means for high-contrast UDVA and low-contrast UDVA did not vary significantly between the 2 groups. However, mean CDVA measured using the high-contrast letter chart was 0.12 logMAR (one line of letters on the chart) worse in the multifocal group than in the monofocal IOL group ($P = .000025$). Moreover, mean CDVA measured with the low-contrast letter chart was 0.13 logMAR (more than one line of letters on the chart) worse in the multifocal group than in the monofocal IOL group ($P = .000039$). The mean differences between low- and high-contrast CDVA and low- and highcontrast UDVA were nearly 2 lines of visual acuity in both IOL groups, with no significant difference between groups.

No significant correlation was detected between disk halo size and mesopic pupil size (Pearson $r = -0.11$ and $r = 0.07$) in each IOL group. Through

Table 2. Monocular uncorrected and corrected distance logMAR visual acuity measured using high-contrast and low-contrast letter charts in eyes implanted with monofocal or multifocal intraocular lenses.

Distance Visual Acuity	Monofocal IOL	Multifocal IOL	*P*
High-contrast			
UDVA	0.08 ± 0.12 (–0.10, 0.38)	0.13 ± 0.08 (0.02, 0.24)	.092
CDVA	0.00 ± 0.06 (–0.10, 0.08)	0.12 ± 0.09 (–0.06, 0.24)	.000025
Low-contrast			
UDVA	0.26 ± 0.12 (0.04, 0.46)	0.33 ± 0.09 (0.18, 0.48)	.065
CDVA	0.18 ± 0.07 (0.04, 0.34)	0.31 ± 0.09 (0.16, 0.48)	.000039

CDVA = corrected distance visual acuity; IOL = intraocular lens; UDVA = uncorrected distance visual acuity
Data are mean ± SD (minimum, maximum)

multiple linear regression, we assessed the relationship between halo radius and distance visual acuity (UDVA and CDVA) measured using high- and low-contrast letter charts in each IOL group. A significant positive correlation ($r = 0.72$) was detected only between halo radius and low-contrast UDVA ($F = 20.96$; $P = .0002$; $R^2 = 52\%$) in the multifocal IOL group (Figure 3). Thus, halo radius increased as low-contrast UDVA worsened (a higher logMAR value indicates worse visual acuity).

To avoid a possible effect of a worse low-contrast UDVA for the recognition task on the halo radius measurement, we also compared halo radii between the IOL groups when low-contrast UDVA was equal to 0.40 logMAR (20/50) or better, a value above the letter size (20/60) for halo size measurement. Mean halo radius was 33.7 arcmin (one ring of the test) larger in the multifocal group (215.19 ± 38.31; n = 16) than in the monofocal IOL group (181.5 ± 54.19 arcmin; n = 16). This difference did not reach statistical significance ($t = -2.03053$; $P = .0512$). However, the statistical power to accept the null hypothesis was only 63%. The significant positive correlation ($r = 0.66$) observed between halo radius and low-contrast UDVA ($F = 10.98$; $P = .0051$; $R^2 = 44$ %) was also maintained in the multifocal IOL group.

DISCUSSION

Numerous studies have addressed visual performance in eyes implanted with diffractive multifocal IOLs, but few investigations have examined disk halo size as an objective outcome in comparison with monofocal IOLs. As far as we are aware, this is the first study to test halo size in patients implanted with a diffractive multifocal IOL. In subjects aged 70 years or older, we show that the mean disk halo radius was significantly greater (35 arcmin of difference, approximately one ring) in individuals who had undergone implantation 6 to 9 months previously with a diffractive multifocal IOL (Acrysof Restor SN6AD1) compared to those who had received an aspheric monofocal IOL (Acrysof IQ SN60WF) also 6 to 9 months previously.

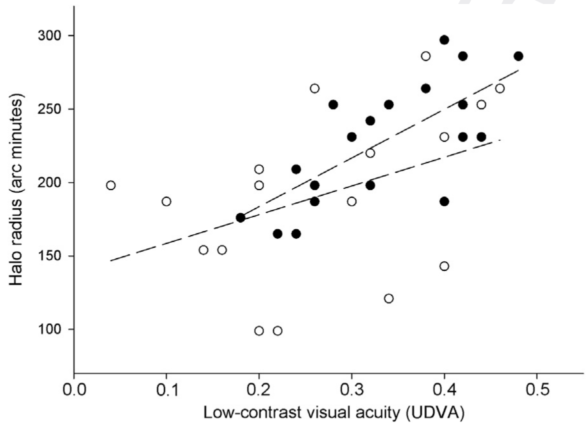

Figure 3. Halo radius (arcminutes) according to uncorrected distance visual acuity (UDVA) (logMAR) measured using low-contrast letter charts in the monofocal and multifocal intraocular lens (IOL) groups. Halo radius (multifocal IOL group) = 117 + 331 × low-contrast UDVA.

Diffractive IOLs use the base lens curvature and the zero and first diffraction orders to divide the amount of light energy over far and near focal points.[3] The drawback is that the focused retinal image provided by one of the lens powers is always overlaid by an out-of-focus image from the second lens power. This unfocused image gives rise to the veil of luminance over the retinal image, as well as to the halos perceived by the subject. The light distribution of the retinal image, or point spread function, is affected by 2 factors: aberrations and scatter. This function has a central narrow, intense peak with a low-intensity peripheral contour. Although the central peak is mainly degraded by wavefront aberrations (lower- and higher-order), scattering affects the point spread function skirts.[21] In other studies, no significant differences were found in total, higher-order, spherical, and coma aberrations when comparing subjects with the Acrysof monofocal IQ IOL and Acrysof Restor SN6AD1 multifocal IOL,[10,22, 23] most likely because of the aspheric apodization of the multifocal IOL. Another possible explanation is the limitations of measuring aberrations in diffractive IOLs. Using Shack-Hartmann aberrometry, Charman et al.[24] found that the multiple wavefronts generated by the diffractive lenses and their dependence on wavelength led to ambiguities in the positions of the spot images and in the form of the derived wavefronts.[24] Mean straylight (scatter) was reported to be significantly greater for the Acrysof Restor SN6AD1 multifocal IOL than the AcrySof IQ SN60WF monofocal IOL 6 months postoperatively.[10] Therefore, the difference in halo radius between our 2 IOL groups (comparable to a difference of 20%) seems to be unaffected by wavefront aberrations but may be the result of the diffractive component of the multifocal IOL. Other multifocal IOL designs, refractive[4] and zonal-progressive,[16] have also been found to induce a significantly larger halo size than monofocal IOLs. Recently, increased light-distortion index or best-fit circle radius of the distortion area have been found after refractive lens exchange with diffractive multifocal IOLs in comparison with monofocal IOL.[25] In our study, the mean halo radius obtained in the monofocal IOL group was similar to the normal mean halo radius reported for phakic eyes for this age group.[18]

In our study, the percentage of patients who rated halos as moderate to severe was significantly greater Q6 in the multifocal IOL group (63.2%) than in the monofocal IOL group (17.6%). Our mean value of 2.5 obtained in the multifocal IOL group is equivalent to the mean reported after presbyopic lens exchange with the Acrysof Restor multifocal IOL in emmetropic patients.[20] However, we detected no significant correlation between disk halo size and self-reported halos in either IOL group. It should be noted that although halo radius is a monocular measurement, halo disturbances were reported for both eyes. Furthermore, whereas self-reported halos in daily life likely refer to uncorrected conditions, halo size measurements were made with spectacle correction. However, we can anticipate that there would be no significant difference between the uncorrected halo and the best-corrected halo because the size of the letters in the halo device (20/60) are clearly above the visual acuity threshold and because the mean BSC was less than 0.25 D in both IOL groups. In addition, halo size and mesopic pupil size showed no correlation. This is likely because mesopic pupil size was measured before the glare source was switched on, and it is possible that the pupil constricted slightly during halo measurements because of the glare source located at 2.5 m.

In this study, mean monocular high- and low-contrast UDVA did not vary significantly in the monofocal and multifocal IOL groups. However, mean monocular high- and low-contrast CDVA were 0.12 and 0.13 logMAR (around one line) significantly worse in the multifocal than in the monofocal IOL group, respectively. Best spectacle correction improved mean high- and low-contrast visual acuity by 0.08 logMAR (4 letters) each in the monofocal group, but failed to improve visual acuity by more than one letter (0.015 and 0.018 logMAR, respectively) in the multifocal group. In the few studies that have compared the Acrysof Restor SN6AD1 multifocal IOL and monofocal IQ SN60WF IOLs,[10,26,27] no significant differences in monocular high-contrast UDVA and high-contrast CDVA, measured using an all-distance vision tester (AS-15, Kowa), were observed between the 2 IOL groups 3 months postoperatively.[26] Likewise, no differences in binocular high-contrast UDVA and high-contrast CDVA were detected 3 months[27] and 6 months postoperatively.[10] In only one of these studies (as in our study) was low-contrast visual acuity examined,[26] and monocular contrast acuity assessed using the CAT-2000 instrument (Menicon) was similar for the monofocal and multifocal IOLs.[26] We observed a similar loss of nearly 2 lines of visual acuity from high-contrast to low-contrast in both IOL groups.

In previous work, we observed that disk halo radius was independent of photopic high- or low-contrast CDVA in phakic healthy subjects.[28] In the present study, halo radius was also not related to high- or low-contrast CDVA or UDVA measured using high-contrast letter charts in both IOL groups, and halo radius was not correlated with low-contrast UDVA in the monofocal IOL group. Similarly, no significant correlations were found between the light-distortion index or best-fit circle radius and postoperative high-contrast UDVA and CDVA in diffractive multifocal IOLs.[25] However, in the present study, a significant correlation was detected between the halo radius and low-contrast UDVA in the multifocal IOL group. This coincides with the finding that retinal straylight, measured with the C-Quant, was significantly correlated with contrast sensitivity in patients implanted with a multifocal IOL.[12] Furthermore, using the iTrace aberrometer a lower modulation transfer function, Q7 that is, worse image contrast, at 5 and 10 cycles per degree was detected in 3.0 mm pupils for the Acrysof Restor SN6AD1 multifocal IOL compared with the AcrySof IQ SN60WF monofocal IOL.[10] However, it should be noted that wavefront measurements using ray-tracing technology through discontinuous bifocal surfaces are limited, because the diffractive behavior demands that the area of the lens illuminated is sufficiently large for adequate summation of secondary wavelets to occur.[24] In our study, halo radius increased as low-contrast UDVA worsened in the multifocal IOL group, likely revealing the greater influence of optical blur (defocus and optical aberrations) of the multifocal lens design. However, low-contrast UDVA could explain only up to 52% of the variance in halo radius.

In summary, the apodized diffractive multifocal IOL gave rise to a larger disk halo size and more halo complaints than the monofocal IOL. However, for the eyes implanted with a multifocal IOL attaining a better low-contrast UDVA, measured disk halos were smaller.

WHAT WAS KNOWN

- Glare and halos are frequent complaints among individuals with multifocal IOLs.

WHAT THIS PAPER ADDS

- The mean size of a disk halo induced by a glare source was significantly greater in patients implanted with a diffractive multifocal IOL than in those with an aspheric monofocal IOL. Halo size was independent of high-contrast visual acuity but increased as low-contrast UDVA worsened in the multifocal IOL group.

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