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Comparison of Higher-Order Aberration and Contrast Sensitivity in Monofocal and Multifocal Intraocular Lenses

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Purpose: The visual performance of pseudophakic eyes depends on the type of intraocular lenses (IOLs) that are implanted. Aspherical and multifocal IOLs have recently been developed to improve visual quality after cataract surgery, but multifocal IOLs can be associated with decreased contrast sensitivity (CS), halos, and glare. This study compares the visual performance of monofocal and multifocal IOLs by measurement of higher-order aberrations (HOAs) and CS values. **Materials and Methods:** HOAs and CS values of 42 eyes with implanted monofocal IOLs and 40 eyes with implanted multifocal IOLs were measured preoperatively and more than 6 months after surgery. In the multifocal IOL group, HOAs and CS values were also measured with addition of a trial lens of - 0.5 diopter (D) to evaluate the compensatory effect on spherical aberration. **Results:** CS values of the multifocal IOL group were significantly lower than those of the monofocal IOL group for all spatial frequencies tested ($p < 0.01$), and the spherical aberration was significantly higher in the multifocal IOL group than in the monofocal IOL group ($p < 0.001$). Addition of a - 0.5 D lens to the multifocal IOL group decreased the difference in CS between the two groups ($p = 0.003$). **Conclusion:** Increased spherical aberration may contribute to lower CS in the multifocal IOL group. In such cases, CS can be improved by addition of a - 0.5 D lens to compensate for the spherical aberration.

Key Words: Higher-order aberration, spherical aberration, contrast sensitivity, multifocal IOL

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INTRODUCTION

Intraocular lenses (IOLs) are designed to provide the best quality of vision after cataract removal. Monofocal IOLs provide excellent postoperative visual quality but spectacles are required to improve near vision. Recently, new types of IOLs such as multifocal and pseudoaccommodative lenses have been developed to reduce the patient's dependence on spectacles, but their optical performance has limited popular use of these IOLs.

Standard visual acuity is a crude measurement of visual performance and cannot adequately represent all aspects of visual function. In many ways, contrast sensitivity (CS) test is expected to be more useful for the accurate evaluation of the visual function.[1] Therefore, objective evaluation of visual performance of these IOLs by wavefront analysis and CS values is required.

Improvement of uncorrected near visual acuity has been achieved with multifocal IOLs, but loss of clarity, low CS, and complaints of halos and glare have been reported.[2-6] The visual phenomena observed by patients after implantation of multifocal IOLs, such as ring or star visual sensations, are mitigated by the addition of a - 0.5 or - 1.0 diopter (D) lens.[7] It has been suggested that the glare, halos, and starburst phenomena reported by pseudophakic patients can be attributed to spherical aberration.[8,9] Yoon et al.[10] reported that spherical aberration is one of the most significant higher-order aberrations (HOAs) that reduce retinal image quality. Furthermore, they proposed that spherical aberration also affects the subjective refraction of defocus and suggested that adding an appropriate amount of defocus could improve the quality of the retinal image when spherical aberration is present.

We conducted the current study to compare the HOAs and CS values between monofocal and multifocal IOL implantation groups. In addition, we measured the HOAs and CS values of patients with multifocal IOL with addition of a trial lens of - 0.5 D to evaluate its compensatory effect on HOA and CS.

MATERIALS AND METHODS

This study was based on 82 eyes of 68 patients who underwent cataract surgery performed from 2000 to 2005 by two surgeons at the Department of Ophthalmology, Severance Hospital, Yonsei University College of Medicine. Forty-two eyes of 36 patients were implanted with monofocal IOLs and 40 eyes of 32 patients were implanted with multifocal IOLs. Patients in the monofocal group received SI40NB (silicone 3 piece, AMO, Santa Ana, CA, USA), whereas patients in the multifocal group received a zonal-progressive Array SA40N (silicone 3 piece, AMO, Santa Ana, CA, USA). All cataract surgeries were performed using topical anesthesia, clear cornea temporal incision, and continuous curvilinear capsulorrhexis. Phacoemulsification was followed by irrigation and aspiration of the cortex and then the IOL was implanted in the capsular bag. All surgeries were completed without any complications.

Biomicroscopic examination, best corrected visual acuities (BCVA), manifest refractions, uncorrected near visual acuities, HOAs, and CS values were measured preoperatively and more than 6 months after surgery. HOAs and CS were measured under photopic conditions to evaluate the patients' visual quality during their daily activities. Near visual acuities were measured with the Rosenbaum near vision card at a distance of 33 cm.

The corrected visual acuities of all pseudophakic eyes included in this study were above 0.6 with the Snellen eye chart. We excluded patients with conditions that could potentially affect visual acuity: systemic or ocular diseases such as diabetes, hypertension, renal diseases, uveitis and macular degeneration, history of ocular surgery or inflammation, and intra-operative or postoperative complications. In addition, eyes with decentered IOLs were excluded from this study.

Contrast sensitivity

CS values were measured using the VCTS® 6500 (Vistech consultants, Inc., Dayton, OH, USA) under photopic conditions (85 cd/m^2) with correction of refractive errors. This test allows presentation of sine-wave gratings of different spatial frequencies. The CS value units were measured for 1.5, 3, 6, 12, and 18 cycles per degree (CPD). Absolute values of CS were obtained for each eye at five spatial frequencies for each group.

Wavefront aberration

HOAs were measured by WaveScan Wavefront™ (VISX, Santa Clara, CA, USA) in photopic conditions (85 cd/m^2) with correction of refractive errors. The mean pupillary size of the patients in this study under photopic condition was 3.8 mm, therefore the WaveScan tests were performed at a pupil size of 4 mm. For each eye, the measurements were repeated at least three times to obtain a well-focused, properly aligned image. Zernike coefficients were taken from WaveScan Wavefront™ and the results were compared between monofocal and multifocal IOL groups. The wavefront analysis for the multifocal IOL group was repeated with a - 0.5 D lens placed in front of the examined eye, positioning the lens on the headrest of WaveScan™.

Statistical analysis

Patients were divided into three groups: monofocal IOL, multifocal IOL, and multifocal IOL with - 0.5 D lens. The independent t-test and paired t-test were used to compare HOAs and CS values between the monofocal and multifocal group, and between the multifocal and multifocal with - 0.5 D lens groups, respectively. Comparisons of individual Zernike coefficients were made using an independent and paired t-test with Bonferroni correction. We also evaluated the correlation between HOAs and CS values by linear regression analysis and determined Spearman's correlation coefficient where 0 indicates no linear correlation and ± 1 indicates perfect linear correlation for the two continuous variables. A p value < 0.05 was considered statistically significant except for HOAs, where a p value of 0.004 was selected as an upper limit. The data were analyzed with SPSS software (Version 11.5 for Windows).

RESULTS

Patient characteristics are shown in Table 1. There were no statistically significant differences in age and sex between the monofocal IOL group and the multifocal IOL group. The BCVA for distance was 0.90 ± 0.11 in the monofocal IOL group and 0.94 ± 0.10 in the multifocal IOL group ($p = 0.13$). The typical uncorrected near visual acuity was J3 for both multifocal and monofocal coefficients ($p < 0.001$).

Addition of a - 0.5 D lens to multifocal IOL IOL groups and was not significantly different between the two groups.

CS was significantly lower in the multifocal IOL group than in the monofocal IOL group ($p < 0.01$ for all spatial frequencies) (Table 2 and Fig. 1). The roots mean square (RMS) errors of HOAs in the multifocal IOL group were significantly higher than in the monofocal IOL group (0.27 ± 0.09 vs.

Table 1. Clinical Characteristics of the Subjects

Group	Monofocal IOL (n = 42)	Multifocal IOL (n = 40)	*p* value
Sex (M : F)	15 : 27	14 : 26	0.95
Age (yrs)	62.93 ± 17.64	64.30 ± 7.51	0.65
Follow up time (months)	18.72 ± 23.10	38.99 ± 14.02	< 0.01
BCVA for distance	0.90 ± 0.11	0.94 ± 0.10	0.13
Near vision	0.48 ± 0.20 (J3)	0.54 ± 0.20 (J3)	0.53
SE (diopters)	- 0.23 ± 0.39	- 0.57 ± 0.80	0.02

IOL, intraocular lens; BCVA, best corrected visual acuity; SE, spherical equivalent.
Values are given as mean ± standard deviation.
Near vision of 0.5 corresponds to J3, 0.65 to J2, 0.8 to J1, and 1.0 to J1+.

Table 2. Comparison of Contrast Sensitivity Values for Monofocal IOL, Multifocal IOL and Multifocal IOL with - 0.5 D Lens Groups

Spatial frequency	Monofocal IOL (n = 42)	Multifocal IOL (n = 40)	Multifocal IOL with - 0.50 D (n = 40)	Diff. A*	Diff. B†	Diff. C‡
1.5 CPD	25.29 ± 9.030	14.79 ± 6.37	19.83 ± 8.01	< 0.01	< 0.01	0.09
3 CPD	52.86 ± 21.95	19.00 ± 7.98	21.00 ± 4.43	< 0.01	< 0.01	< 0.01
6 CPD	43.71 ± 16.29	10.14 ± 6.33	16.00 ± 5.22	< 0.01	< 0.01	< 0.01
12 CPD	31.43 ± 22.83	1.43 ± 2.30	3.33 ± 2.46	< 0.01	< 0.01	< 0.01
18 CPD	17.29 ± 12.00	0.36 ± 1.31	0.83 ± 1.95	< 0.01	0.17	< 0.01

CPD, cycles per degree.
The contrast sensitivity was significantly lower in the multifocal IOL group than in the monofocal IOL group for all spatial frequencies. With the exception of 18 CPD, addition of a -0.5 D lens to multifocal IOL implanted eyes significantly improved contrast sensitivities. Values are given as mean ± standard deviation. The examined eyes were uncorrected.
*Difference between monofocal IOL and multifocal IOL (p value).
†Difference between multifocal IOL and multifocal IOL with - 0.5 D lens (p value).
‡Difference between monofocal IOL and multifocal IOL with - 0.5 D lens (p value).

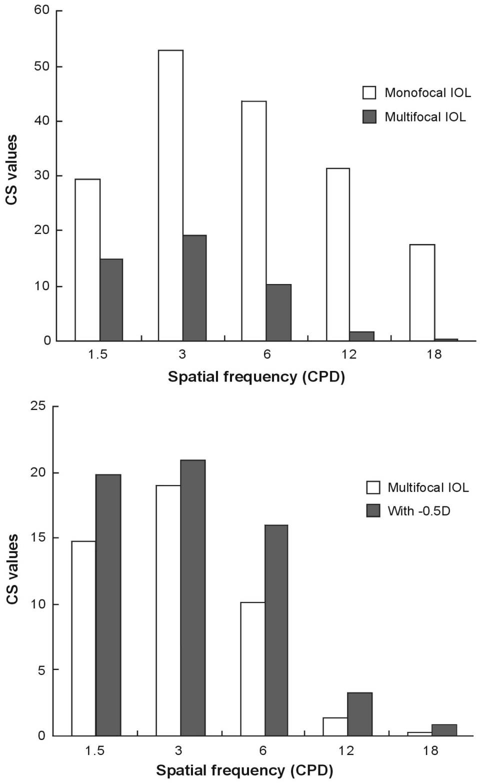

Fig. 1. Comparison of Contrast Sensitivity Values of Monofocal IOL, Multifocal IOL and Multifocal IOL with -0.5 D Lens.

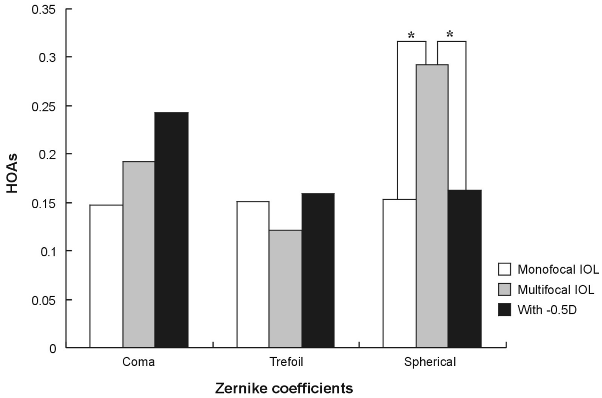

Fig. 2. Comparison of Higher-order Aberrations of Monofocal IOL, Multifocal IOL and Multifocal IOL with - 0.5 D Lens. The increased spherical aberration observed in the multifocal IOL group was decreased to a level equivalent to that of the monofocal IOL group by addition of a - 0.5 D lens (p = 0.750). *Statistically significant difference ($p < 0.004$).

0.12 ± 0.08 respectively; $p < 0.001$) (Table 3 and Fig. 2). The spherical aberrations were significantly higher in the multifocal group than in the monofocal group based on the individual Zernike implanted eyes significantly improved CS ($p < 0.01$) at all spatial frequencies except for 18 CPD. Addition of the lens significantly decreased

Table 3. Comparison of Higher-order Aberrations of Monofocal IOL, Multifocal IOL, and Multifocal IOL with - 0.5 D Lens

	Monofocal IOL (n = 42)	Multifocal IOL (n = 40)	Multifocal IOL with - 0.50 D (n = 40)	Diff. A*	Diff. B†	Diff. C‡
Total RMS	0.31 ± 0.09	0.48 ± 0.07	0.56 ± 0.08	< 0.001	0.011	< 0.001
RMS HOA	0.12 ± 0.08	0.27 ± 0.09	0.38 ± 0.20	< 0.001	0.014	< 0.001
Wavefront aberration						
Coma	0.15 ± 0.08	0.19 ± 0.10	0.24 ± 0.15	0.059	0.010	0.049
Trefoil	0.15 ± 0.06	0.12 ± 0.04	0.16 ± 0.06	0.039	0.407	0.737
Spherical	0.15 ± 0.06	0.29 ± 0.11	0.16 ± 0.08	< 0.001	0.003	0.685

RMS, root mean square of Belle aberration maps.
The RMS error of higher-order aberrations and spherical aberrations were significantly higher in the multifocal IOL group than that in the monofocal IOL group. Addition of a - 0.5 D lens significantly decreased spherical aberrations in the multifocal IOL group. Values are given as mean ± standard deviation. The examined eyes were uncorrected. P value less than 0.004 was considered statistically significant for Zernike coefficients.
Independent t-test was used for comparison of HOAs between the monofocal and multifocal IOL group and between the monofocal IOL and multifocal IOL with - 0.5 D lens group, and paired t-test was used for comparison between multifocal IOL and multifocal IOL with - 0.5D lens groups.
*Difference between monofocal IOL and multifocal IOL group (p value).
†Difference between multifocal IOL and multifocal with - 0.5 D lens group (p value).
‡Difference between monofocal IOL and multifocal IOL with - 0.5 D lens group (p value).

Table 4. Correlation between Contrast Sensitivity Values and Higher-order Aberrations

Wavefront aberration	Standardized coefficients β at each spatial frequency				
	1.5 CPD	3 CPD	6 CPD	12 CPD	18 CPD
Coma	- 0.464	- 0.802	- 0.731	- 0.800	- 0.819
Spherical	- 0.875	- 0.578	- 0.665	- 0.581	- 0.555

CPD, cycles per degree.
Significant negative correlation between contrast sensitivity values and spherical aberrations was noted. Coma aberrations also showed negative correlation to contrast sensitivity values. Trefoil aberrations were excluded from regression analysis because of low correlation with contrast sensitivity values.

spherical aberration of the multifocal IOL group (p = 0.003) and there was no significant difference in spherical aberration between the monofocal IOL and the multifocal IOL with the - 0.5 D lens group (p = 0.685).

The correlation between HOAs and CS values was evaluated at five spatial frequencies for all groups combined (Table 4). The results showed significant negative correlation between CS values and both spherical aberrations and coma aberrations. Trefoil aberrations showed low correlation with CS values and were excluded from regression analysis.

DISCUSSION

This study demonstrates that CS values are decreased and HOAs are increased in the multifocal IOL group compared with the monofocal IOL group. Addition of a - 0.5 D lens reduced spherical aberration and improved CS in the multifocal IOL group.

The BCVA for distance was above 0.6 with the Snellen eye chart in both monofocal IOL and multifocal IOL groups. Several other reports have demonstrated that near visual acuity is better in multifocal IOL implanted patients than in patients with monofocal IOLs,[11,12] but in this study uncorrected near visual acuity of the multifocal IOL group was not superior to that of the monofocal IOL group. We presume that the difference in these results can be attributed to various refractive statuses in pseudophakic eyes, such as myopia in monofocal IOL implanted eyes. In addition, apparent accommodation (pseudoaccommodation) related to corneal multifocality could contribute to the good near visual acuity in the monofocal IOL group.[13,14] The negative effects of refractive status in pseudophakic eyes could be clarified by comparison of near visual acuity with a distance correction between the monofocal and multifocal IOL group.

CS values were significantly lower for all spatial frequencies in the multifocal IOL group compared with the monofocal IOL group ($p < 0.01$). Previous studies have also reported a decreased CS in multifocal IOL implanted eyes[2,4,15-17] and it has been reported that AMO Array multifocal IOLs might cause more glare and lower CS than monofocal IOLs.[18] Bellucci[19] reported that patient satisfaction was no higher with multifocal IOLs than with monofocal IOLs and attributed poor visual performance to the reduction of CS and the presence of halos.

In this study, we show that HOAs, especially spherical aberrations, were increased significantly in the multifocal IOL group compared with the monofocal IOL group ($p < 0.001$). Montés-Micó et al.[11] suggested that a possible cause of reduced CS in multifocal IOLs is the division of light energy through two focal points produced by the multifocal IOL, implying that spherical aberration plays a role in decreasing CS in multifocal IOL implanted eyes. Our study implicated that there is a significant relationship between decreased CS and increased spherical aberration in the multifocal IOL group.

Visual phenomena, such as glare and halos, in multifocal IOL implanted eyes are known to be mitigated by addition of a - 0.5 D or - 1.0 D lens.[7] The addition of an appropriate amount of defocus in cases of spherical aberration could improve retinal image quality compared with the same degree of spherical aberration with zero defocus.[10] Our data confirm that addition of a - 0.5 D lens in the multifocal IOL group significantly reduced spherical aberration and improved CS value.

Regression analysis revealed a strong correlation between HOAs, such as coma and spherical aberration, and CS values. However, optical aberrations analysis did not show a significant difference in coma aberrations between the monofocal and multifocal IOL group, suggesting that spherical aberrations induced by multifocal IOL contribute more to the reduction in CS than coma aberrations do.

Addition of a negative diopter lens such as the - 0.5 D lens used in this study reduces spherical aberration, but also influences near visual acuity. Although addition of a - 0.5 D lens makes near vision worse in the general population, for patients with multifocal IOL implanted eyes the negative effect on near vision was less important than the reduction of the loss of clarity, low-CS, and visual phenomena of halos and glare that affect far vision required for daily activities such as driving.

Residual refractive errors, astigmatism, and delicate decentration of the IOL relative to the pupil might impact on the visual performance of the patients. Furthermore, spherical aberration would be expected to increase in multifocal IOL because a large portion of the light energy is out of focus. Combined with the effect of corneal multifocality on visual function, this may influence the measured aberration caused by different IOLs.[14] In addition, this study was performed only in photopic conditions, and the Array SA40N multifocal lens is currently being replaced by the new generation multifocal IOL. Despite these limitations, the results of this study do indicate one possible way in which the visual quality of pseudophakic eyes may be improved. Further studies using the newly developed multifocal IOLs that are generally regarded as superior to the Array lens are now needed.

In conclusion, decreased CS is associated with low satisfaction with visual performance in multifocal IOL implanted patients, and spherical aberration appears to be the key contributor to reduced CS in these patients. Alleviation of spherical aberration by addition of a - 0.5 D lens resulted in improved CS, therefore improvement in functional vision of multifocal IOL implanted patients may be possible if new multifocal IOLs are designed to reduce spherical aberration.

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