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# Higher-order aberrations of lenticular opacities

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**Purpose:** To measure and quantify higher-order aberrations induced by different types of lenticular opacities.

**Setting:** Department of Ophthalmology, University of Auckland, and Department of Ophthalmology, Auckland Public Hospital, Auckland, New Zealand.

**Methods:** Patients with lenticular opacities were recruited from outpatient clinics of a major tertiary referral center for ophthalmology. Patients were included if they had clinically evident, mild to moderate lenticular opacity with no coexisting ocular pathology. Patients were examined using standard preoperative techniques with additional assessment by wavefront aberrometry (Zywave®, Bausch & Lomb) and Scheimpflug photography (EAS-1000, Nidek). For comparison, 20 eyes of 10 subjects with no lenticular opacity (control group) were recruited and assessed in an identical manner.

**Results:** Thirty persons were recruited and 40 eyes assessed, 20 with lenticular opacities. Ten eyes had predominantly cortical opacification, and 10 had mainly nuclear opacification. In eyes with predominantly cortical opacification, the mean logMAR uncorrected visual acuity (UCVA) was  $0.5 \pm 0.2$  (SD) (6/18 Snellen equivalent) and the mean logMAR best spectacle-corrected visual acuity (BSCVA),  $0.2 \pm 0.2$  (6/9). Analysis of aberrometry data for a 6.0 mm pupil in this group revealed an increase in coma of cosine phase ( $Z_3^1$ ,  $P = .06$ ) and tetrafoil of cosine phase ( $Z_4^4$ ,  $P = .07$ ) compared to eyes in the control group. Eyes with predominantly nuclear opacification had a mean logMAR UCVA of  $0.7 \pm 0.2$  (6/30) and a logMAR BSCVA of  $0.4 \pm 0.2$  (6/15). Aberrometry data for this cohort for a 6.0 mm pupil showed a statistically greater amount of spherical aberration ( $Z_4^0$ ,  $P = .001$ ) and tetrafoil of cosine phase ( $Z_4^4$ ,  $P = .005$ ;  $Z_4^{-4}$ ,  $P = .004$ ).

**Conclusions:** This pilot study suggests that different types of early lenticular opacities induce different wavefront aberration profiles. Predominantly cortical opacification produced an increase in coma and nuclear opacification induced an increase in spherical aberration compared to eyes without opacities. Both types of lenticular opacities also induced a higher amount of tetrafoil. This could explain the significant visual symptoms in patients with early cataract and relatively good high-contrast Snellen acuity.

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Cataract is the leading cause of preventable blindness worldwide,<sup>1</sup> and cataract surgery is the most common surgical procedure in those older than 65 years in New Zealand<sup>2</sup> and the United Kingdom.<sup>3</sup>

In current clinical practice, assessment of monocular visual acuity is usually the primary test of visual

function in determining the need for cataract surgery<sup>4</sup> and for evaluating its success. This is generally assessed using a Snellen chart composed of high-contrast letters placed 6 m (20 feet) from the patient in a glare-free environment. However, this is not representative of normal everyday situations experienced by the elderly; thus, it is not surprising that patients' perception of their visual function in the presence of cataract does not correlate well with their measured level of visual acuity. A study by Elliott and coauthors<sup>5</sup> revealed little correlation between subjective visual disturbance and

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objective visual acuity measurements. This suggests that the best assessment and prioritization of patients for cataract surgery require information in addition to high-contrast visual acuity.

In an attempt to address the deficiencies in assessing visual impairment secondary to cataract, visual function scales were developed to yield more information on the functional limitation of patients with cataract; these include the VF-14<sup>6</sup> and Catquest questionnaires.<sup>7-9</sup> In a further attempt to assess functional disability, the Cataract Symptom Scale<sup>3</sup> was developed; this interviewer-administered questionnaire has been used in the United Kingdom. However, neither the Catquest nor Cataract Symptom Scale has been widely adopted in clinical practice to assess visual function before or after cataract surgery given the time frame required to complete the questionnaires.

The more widespread introduction of wavefront aberrometry into clinical ophthalmic practice has provided a technique that can be used to objectively assess visual performance. This technology has been used widely in clinical ophthalmology in the refinement of corneal refractive surgery.<sup>10</sup> We performed this pilot study to determine whether this tool can be used to assess the visual function in patients with cataract, providing information in addition to high-contrast Snellen acuity upon which to base the timing of cataract surgery.

## Patients and Methods

This prospective study was performed in the Department of Ophthalmology, University of Auckland, New Zealand. All participants provided fully informed consent, and the Auckland Ethics Committees approved the study protocol.

Patients were recruited from outpatient clinics of Auckland Public Hospital, the major tertiary referral center for ophthalmology in New Zealand. They were selected on the basis of clinically evident lens opacification with no coexisting ocular pathology. A standard preoperative ophthalmic assessment was performed in all patients and included vision and visual acuity obtained using a standard 4 m logMAR chart, refraction determined by autorefractometry, anterior segment slitlamp biomicroscopy, dilated pupil fundus examination, intraocular pressure measurement, and keratometry and axial length measurements (Tomey AL-2000). The uncorrected visual acuity (UCVA) and best spectacle-corrected visual acuity (BSCVA) were recorded as logMAR units (Snellen equivalent). Additional assessment was performed using a Hartmann-Shack aberrometer (Zywave®, Bausch & Lomb) and a Scheimpflug

camera (EAS-1000, Nidek) by a single examiner (N.S.). The latter measurements were performed before contact investigations that might alter the corneal epithelium or tear film were performed.

Wavefront aberrometry and Scheimpflug assessment were performed after the pupil was pharmacologically dilated to larger than 6.0 mm. Dilation was achieved with tropicamide 1% drops and phenylephrine 2.5% drops (Minims®). For wavefront aberrometry assessment, 3 readings were acquired in a low-illumination room for each eye in the study. The best acquisition of the 3 readings was determined by patient compliance and the clearest centroid image. Once the best image was ascertained, the aberrometry data for a 6.0 mm pupil were used for further analysis.

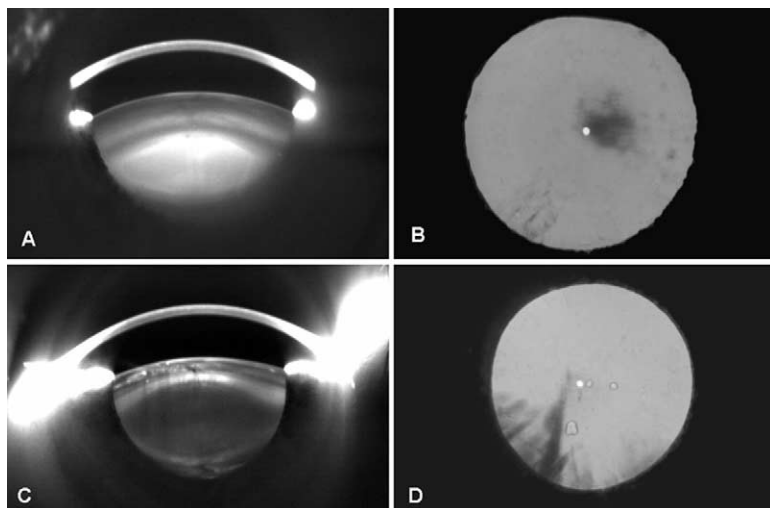
The Zywave mathematically computes the amplitude of each Zernike polynomial using the deviation from each centroid point within the wavefront. This technique of measuring and quantifying higher-order aberrations using a Scheiner-Hartmann-Shack wavefront sensor has been described by Thibos.<sup>11</sup> In all cases, the polynomials for a 6.0 mm pupil were used and corrected purely in terms of a “-” or “+” sign convention (not magnitude); this was done so the analysis would be consistent with Thibos’ technique (see discussion). The root mean square (RMS) used for analysis was computed by the Zywave. The RMS error, using the polynomials produced by the Zywave, was calculated as the square root of the sum of the squares of each polynomial.

Scheimpflug photography was done to standardize the assessment of the severity of the opacity, confirming the clinical findings (Figure 1). For all eyes, 4 slit images were acquired at 0, 45, 90, and 135 degrees. Analysis was performed using the proprietary software provided with the EAS-1000 system. The peak density of the opacity for each image was obtained.

Patients were excluded if the lenticular opacity was too dense to obtain a complete aberrometry image, if they were unable to comply with the investigations because of immobility or other medical causes, or if they had a pharmacological pupil diameter smaller than 6.0 mm.

For comparison, 20 eyes of 10 subjects with no clinically detectable ocular pathology were recruited and served as a control group for aberrometry assessments. These subjects were mainly staff members of the Department of Ophthalmology, University of Auckland. Their assessment was identical to that of eyes with lens opacification and included visual acuity using a standard 4 m logMAR chart, autorefractometry, fully dilated clinical examination, wavefront aberrometry, and Scheimpflug photography. Eyes in the control group were pharmacologically dilated using a regimen identical to that used in the lens opacification groups. However, contact investigations by applanation tonometry and A-scan ultrasound measurement of axial length were not performed in the control group.

Statistical analysis was performed by a medical statistician at the University of Auckland. Analysis of aberrometry



**Figure 1.** (Sachdev) Scheimpflug slit (*left*) and retroillumination (*right*) images showing predominantly nuclear opacification (A and B) and predominantly cortical opacification (C and D).

data was initially done using a mixed linear regression model, with the right and left eyes as a repeated measure and each group as an explanatory variable (ie, eyes with cortical lens opacification, eyes with nuclear opacification, and normal eyes as separate groups). To determine the statistically significant difference between normal eyes (control group) and the 2 groups with lenticular opacities, a Dunnett test was used to compare the 2 lens opacity groups with the control group when the initial analysis yielded evidence of a group effect. Separate analyses were performed for each outcome measure (ie, each polynomial). A 5% significance level was used for all statistical analyses.

## Results

The inclusion and exclusion protocols were applied to 120 patients. Of these, 20 patients (20 eyes, 8 right and 12 left) with early lens opacities met all study criteria. Twenty eyes (10 right and 10 left) without opacities (control group) were also assessed. All patients with lens opacification had cortical or nuclear opacities to varying degrees. Ten eyes had predominantly nuclear opacification, and 10 had predominantly cortical opacification.

The mean age of patients with lens opacities was 77.6 years; 70% were women. The mean age in the cortical opacification group was 76.7 years (range 58.0 to 89.0 years) and in the nuclear opacification group, 78.6 years (range 71.2 to 85.4 years). The control group had a younger mean age (32.9 years; range 26.5 to 40.1 years) than the 2 lens opacification groups.

### *Predominantly Cortical Opacification*

In patients with predominantly cortical opacification, the mean UCVA was  $0.5 \pm 0.2$  (SD) (6/18) and

the mean BSCVA,  $0.2 \pm 0.2$  (6/9). The mean spherical equivalent (SE) refraction was  $-1.00 \pm 2.05$  diopters (D).

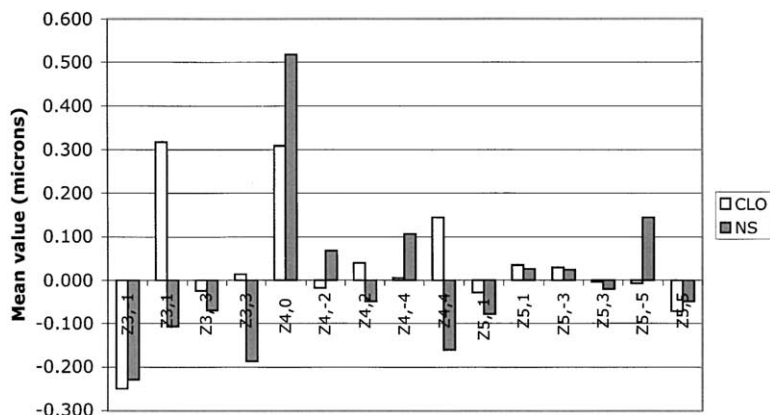
For a standard 6.0 mm pupil, the most prominent of all aberrations was defocus ( $Z_2^0$ ), with a mean value of  $1.185 \pm 3.239$   $\mu\text{m}$ . This was followed by Cartesian astigmatism ( $Z_2^2$ ), with a mean value of  $0.883 \pm 0.676$   $\mu\text{m}$  (Figure 2).

Coma of cosine phase ( $Z_3^1$ ) contributed most to the higher-order aberration profile, yielding a mean value of  $0.317 \pm 0.728$   $\mu\text{m}$ ; this approached statistical significance compared to the mean in the control group ( $P = .06$ ). In descending order of magnitude, this was followed by spherical aberration ( $Z_4^0$ ) (mean  $0.308 \pm 0.267$   $\mu\text{m}$ ;  $P = .07$ ) and coma of sine phase ( $Z_3^{-1}$ ) (mean  $-0.249 \pm 0.489$   $\mu\text{m}$ ); there were significant increases in these values compared to those in the control group. Tetrafoil of cosine phase ( $Z_4^4$ ) had a mean value of  $0.146 \pm 0.154$   $\mu\text{m}$  ( $P = .07$ ). The mean RMS error of all aberrations in the cortical opacification group was  $3.079$   $\mu\text{m}$  and the mean RMS of the higher-order aberrations,  $0.993$   $\mu\text{m}$  (Figure 2 and Table 1).

### *Predominantly Nuclear Opacification*

In eyes with predominantly nuclear opacification, the mean UCVA was  $0.7 \pm 0.2$  (6/30) and the mean BSCVA,  $0.4 \pm 0.2$  (6/15). The mean SE refraction was  $-2.50 \pm 2.09$  D.

For a 6.0 mm pupil, defocus ( $Z_2^0$ ) was the most predominant of all aberrations, with a mean value of  $2.849 \pm 3.859$   $\mu\text{m}$ . Cartesian astigmatism ( $Z_2^2$ ) was next, with a mean value of  $0.455 \pm 0.958$   $\mu\text{m}$  (Figure 2).



**Figure 2.** (Sachdev) Comparison of higher-order polynomials (mean values) between patients with predominantly cortical lens opacification (CLO) (n = 10) and patients with predominantly nuclear lens opacification (NS) (n = 10) (Z3,-1 = coma of sine phase; Z3,1 = coma of cosine phase; Z4,0 = spherical aberration; Z4,4 = tetrafoil of cosine phase).

For a 6.0 mm pupil, spherical aberration ( $Z_4^0$ ) was the most predominant higher-order aberration, with a mean value of  $0.518 \pm 0.486 \mu\text{m}$ ; this was statistically significantly higher than the mean in the control group ( $P = .001$ ). This was followed by coma of sine phase ( $Z_3^{-1}$ ), with a mean value of  $-0.228 \pm 0.347 \mu\text{m}$ , and trefoil of cosine phase ( $Z_3^3$ ), with a mean value of  $-0.186 \pm 0.520 \mu\text{m}$ . These aberrations were not statistically different from those in the control group ( $Z_3^3$ ,  $P = .48$ ). Tetrafoil of cosine phase ( $Z_4^4$ ) and tetrafoil of sine phase ( $Z_4^{-4}$ ) had a mean value of  $-0.160 \pm 0.339 \mu\text{m}$  and  $0.107 \pm 0.224 \mu\text{m}$ , respectively. Both were statistically significantly higher than the means in the control group ( $P = .005$  and  $P = .004$ , respectively). The RMS error of all aberrations in the nuclear opacification group was  $4.192 \mu\text{m}$  and the RMS error of the higher-order aberrations,  $1.120 \mu\text{m}$  (Figure 2 and Table 1).

*No Lenticular Opacification*

In eyes with no lenticular opacification (control group), the mean UCVA was  $0.4 \pm 0.5$  (6/15) and

the mean BSCVA,  $0.0 \pm 0.1$  (6/6). The mean SE refraction was  $-2.13 \pm 2.66$ .

For a 6.0 mm pupil, defocus was the most predominant of all aberrations, with a mean value  $2.648 \pm 3.477 \mu\text{m}$ . Cartesian astigmatism was next, with a mean value of  $0.445 \pm 0.958 \mu\text{m}$  (Figure 3).

Spherical aberration ( $Z_4^0$ ), with a mean value of  $0.150 \pm 0.124 \mu\text{m}$ , contributed the most to the higher-order aberration profile. This was followed by trefoil of sine phase, with a mean value of  $-0.139 \pm 0.227 \mu\text{m}$ . The total RMS error for all aberrations in the control group was  $3.06 \mu\text{m}$  and the RMS error of the higher-order aberrations,  $0.40 \mu\text{m}$  (Table 1).

**Discussion**

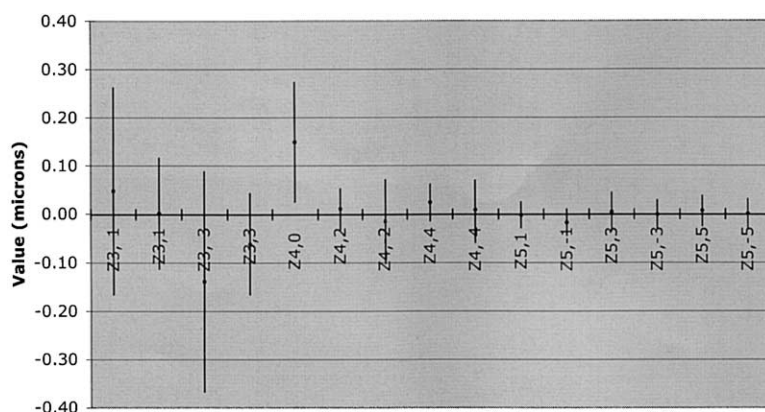
The introduction of wavefront technology to the wider clinical arena of ophthalmology provides a potentially unique tool for the measurement and quantification of higher-order aberrations emanating from a human eye. This technology has been used to measure

**Table 1.** Differences in results between groups.

Parameter	Mean $\pm$ SD ( $\mu\text{m}$ )		P Value*	Mean $\pm$ SD ( $\mu\text{m}$ )	
	Control (n = 20)	Mainly Cortical (n = 10)		Mainly Nuclear (n = 10)	P Value*
Total RMS	3.060	3.079	—	4.192	—
RMS HOA	0.397	0.993	—	1.120	—
Aberration					
Coma $Z_3^{-1}$	$0.002 \pm 0.114$	$0.317 \pm 0.728$	.06	$-0.106 \pm 0.600$	.23
Spherical $Z_4^0$	$0.150 \pm 0.124$	$0.308 \pm 0.267$	.70	$0.518 \pm 0.486$	.001
Tetrafoil $Z_4^4$	$0.009 \pm 0.04$	$0.005 \pm 0.201$	.56	$0.107 \pm 0.224$	.004
Tetrafoil $Z_4^{-4}$	$0.024 \pm 0.06$	$0.146 \pm 0.154$	.07	$-0.160 \pm 0.339$	.005

RMS = root-mean-square error; RMS HOA = root-mean-square error of higher-order aberrations

\*Compared with control group



**Figure 3.** (Sachdev) Means and standard deviations of higher-order polynomials in eyes without lenticular opacities (control group; N = 20).

and quantify aberrations induced by corneal pathology such as keratoconus<sup>12</sup> and has recently been widely used in customizing excimer laser refractive surgery.<sup>13,14</sup>

The use of this technology to measure and quantify aberrations induced by lens opacities is limited. Only 2 studies previously addressed this issue. Kuroda et al.<sup>15</sup> initially documented the higher-order aberrations of 1 nuclear cataract and 1 cortical cataract. They report that nuclear opacification induced negative spherical-like aberrations, defined as the 4th-order component ( $S_4$ ) + the 6th-order component ( $S_6$ ), and that cortical opacification induced a more coma-like aberration, defined as the 3rd-order component ( $S_3$ ) + the 5th-order component ( $S_5$ ), with the polarity of the spherical-like aberration positive. In a subsequent publication of a larger series, Kuroda et al.<sup>16</sup> correlated contrast sensitivity, average lens density measured and analyzed by Scheimpflug photography, corneal aberrations assessed by fitting a Placido disk onto the aberrometer, and wavefront aberrations of the whole eye (referred to as ocular total higher-order aberrations) in 6 eyes with nuclear cataract and 18 eyes with cortical cataract. The results were compared with those in 9 normal eyes. The authors found that corneal aberrations did not significantly differ between normal eyes and eyes with lens opacities, whereas the wavefront aberrations of the whole eye were significantly more pronounced in eyes with lens opacities. Of particular note, in the latter study,<sup>16</sup> nuclear opacities always induced negative spherical aberration, whereas cortical cataracts induced positive spherical aberration.

There are several considerations regarding the 2 studies by Kuroda et al.<sup>15,16</sup> Assessing the cornea by fitting a Placido disk onto a Hartmann-Shack sensor

measures only aberrations attributed to the anterior corneal surface, whereas the posterior corneal surface contributes approximately 13% to the aberration status of the whole eye. Second, the method of aberrometry analysis performed in their study was unique. Indeed, Kuroda et al. refer to coma-like aberrations as the addition of  $S_3 + S_5$ , with  $S_3$  defined as the RMS of all 3rd-order aberrations. Therefore, coma-like aberrations are simply the sum of the RMS of all 3rd-order and 5th-order aberrations and spherical-like aberrations are all 4th-order aberrations. Therefore, although Kuroda et al. conclude that nuclear opacification induces a spherical-like aberration, this is not attributable to the spherical aberration polynomial  $Z_4^0$  in isolation. In terms of comparison, Kuroda et al. used polynomials for the central 7.0 mm and a different commercially available aberrometer than we used in this study, although both aberrometers follow the same optical principle in formulating the aberration status of the eye.

A unique feature of the Zywave is that the wavefront error is measured identically but opposite to that described by Thibos.<sup>17</sup> It is measured from the wavefront emanating from a human eye to the ideal reference wave rather than commencing measurement from the reference wave to the measured wavefront. The result is that the numerical values are identical, but with opposite-sign convention. For ease of comparison, all analyses we performed were corrected in terms of sign convention to be consistent with Thibos.

In the current study, all lens opacities were mixed in origin but were predominantly nuclear or predominantly cortical to varying degrees. Cataracts were graded according to their clinical appearance on slitlamp biomicroscopy, which was confirmed with Scheimpflug

photography analysis. Scheimpflug photography is a well-established imaging tool for the assessment of the anterior segment, in particular in eyes with lenticular opacities.<sup>18</sup> It is an objective, precise technique for in vivo measurement and quantification of lens density.<sup>19</sup>

In eyes with primarily cortical opacification, the mean BSCVA was 6/9, with an increase in coma of the cosine phase ( $P = .06$ ). Although this increase was not statistically significant, we believe this trend warrants further investigation given the small sample size ( $n = 10$ ). The second aberration contributing most to the overall wavefront was spherical; however, this was not significantly higher than in normal eyes. Interestingly, tetrafoil of cosine phase ( $Z_{4,4}$ ), with a mean value of  $0.146 \mu\text{m}$  in the cortical opacification group, was the fourth highest aberration and produced a significance ( $P = .07$ ) that was not anticipated.

In eyes with primarily nuclear opacification, even though the mean BSCVA was 6/15, the spherical aberration was statistically significantly higher than in normal eyes ( $P = .001$ ), which one might anticipate in eyes with nuclear opacities. Similar to eyes with cortical opacification, 4th-order aberrations were significantly high in the nuclear opacification group, with the tetrafoil of cosine phase ( $Z_{4,4}$ ) having a  $P$  value of 0.005 and tetrafoil of sine phase ( $Z_{4,-4}$ ) having a  $P$  value of 0.004.

This increase in 4th-order aberrations, in particular tetrafoil, was seen in both groups with mixed lenticular opacities. However, it was statistically significant in those with predominantly nuclear opacification and minimal cortical opacification. However, theoretically, the increase in tetrafoil seen in eyes with predominantly cortical opacification could be artifactual as a result of the behavior of Zernike polynomials. Because the polynomial set is orthogonal, certain terms can be generated to compensate for other terms that may have been created. For example, in the case of coma, if there is an aberration source on 1 side of the pupil center, an equal but opposite aberration is mathematically created 180 degrees away. To minimize this artifactual effect, other Zernike terms, such as tetrafoil in this case, may be increased.

The mean RMS of the higher-order aberrations appears to increase with the presence of lenticular opacities, more so with nuclear than cortical in the current study. Indeed, nuclear opacification induced 3 times greater higher-order aberration and cortical opacifica-

tion induced approximately twice the amount of mean higher-order aberration compared to control eyes.

Overall, the increase in total RMS with both types of opacities was smaller than the increase in higher-order aberrations. However, this is largely due to the variation in the spherical and cylindrical refractive errors (lower-order aberrations) between patients. Some of the increase in eyes with lenticular opacities may be related to age differences. McLellan and coauthors<sup>20</sup> report that an increase in age of 40 years (22 to 62 years) is associated with an increase in RMS from  $0.70$  to  $1.00 \mu\text{m}$ . However, the objective of our study was to compare eyes with cataract and "normal" eyes. It is difficult to identify an age-matched group older than 60 years without any form of lens opacity.

## Conclusion

Wavefront technology provides a unique tool for measuring and quantifying the aberrations produced by the eye as a whole optical system. In this pilot study, we used this technology to assess visual function in patients with lenticular opacities. The preliminary results suggest that nuclear opacification induces spherical aberration and cortical opacification induces coma, with both forms of cataract inducing varying amounts of tetrafoil.

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