Effect of Chromatic Aberration on Contrast Sensitivity in Pseudophakic Eyes

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Objective: To evaluate the effect of chromatic aberrations in pseudophakic eyes with various types of intraocular lenses (IOLs).

Patients and Methods: The study included 51 eyes of 33 patients who underwent cataract surgery. The eyes were divided into 3 groups according to the material from which their IOL was made: group 1, polymethyl methacrylate; group 2, silicone; and group 3, an acrylate/methacrylate copolymer. Ten normal phakic control eyes (group 4) underwent the same examination. Best-corrected distance visual acuity and contrast sensitivity were measured under white light and monochromatic light with wavelengths of 470 nm, 549 nm, and 630 nm, with the best correction under white light.

Results: There were no significant differences in best-corrected visual acuity and contrast sensitivity under the 549-nm monochromatic light in any group. However, under both white multichromatic light and 470- and 630-nm monochromatic light, the mean contrast sensitivity in group 3 tended to be lower, sometimes significantly, than in the other IOL groups.

Conclusions: Our results showed that longitudinal chromatic aberrations of some IOLs may degrade the quality of the retinal image. Attention must be paid to the detailed optical performance of IOL materials to achieve good visual function.


THE REFRACTIVE indexes of the ocular media are wavelength dependent, and consequently the refractive power of the human eye varies across the visible spectrum. For example, when multichromatic light such as white light passes through the lens, different wavelengths of the light focus on different points of the ocular media. This chromatic dispersion results in chromatic aberrations, and the retinal image is blurred, reducing contrast. Chromatic aberrations, especially longitudinal chromatic aberrations (LCAs), are also thought to be related to various physiologic functions, such as accommodative control\(^1\) and resolution and depth of focus.\(^2\) Therefore, it is important for the physiologic function of the optical system to remain as close as possible to that of the normal eye. In the normal human eye, the cornea and lens are primarily responsible for chromatic aberrations; the contribution of the crystalline lens to chromatic aberrations is reported to be about 28.5% of the entire ocular media.\(^3\) If the chromatic aberration becomes larger and exceeds the normal range, it could degrade the quality of the retinal image and affect visual function.

The chromatic aberrations of intraocular lenses (IOLs) depend on the Abbe number of the optical material. The smaller the Abbe number, the larger the chromatic aberration and the lower the quality of the retinal image. In recent years, small-incision surgery followed by IOL implantation has become the primary technique of cataract surgery. Different types of IOL optical materials have been developed to enable IOLs to be implanted through a smaller incision. Consequently, some materials are being used with Abbe numbers that are far different from that of the human lens. Regarding IOL materials presently available, the Abbe number is smaller in the acrylate/methacrylate copolymer and high refractive index silicone than in polymethyl methacrylate (PMMA) or normal human lenses. Therefore, more degradation of the retinal image can occur in pseudophakic eyes that have been implanted with IOLs made from these materials.

In this study, we investigated the effect of LCAs on contrast sensitivity in pseudophakic eyes with various kinds of IOLs.
PATIENTS AND METHODS

This study was conducted at the National Tokyo Medical Center in Tokyo, Japan. Subjects were recruited retrospectively from among patients who underwent phacoemulsification and aspiration followed by IOL implantation at the hospital from December 1997 through December 1999. Patients with either preoperative systemic or ocular, intraoperative, or postoperative complications were excluded. Informed consent was obtained from each patient by one of the investigators (T.N.) before enrollment in the study.

Continuous curvilinear capsulorrhexis was performed in all cases, and IOLs were implanted in the capsular bag. The implanted IOLs were well centered and were not tilted postoperatively. The examination was performed at least 1 month after surgery. Fifty-one eyes of 33 patients were included in this study, and the mean ± SD follow-up period was 4.9 ± 6.9 months (range, 1-39 months).

The patients were divided into 3 groups according to the model of IOL implanted: group 1, 811C (Pharmacia & Upjohn, Tokyo); group 2, AQ110NV (CanonStaar Inc, Tokyo); and group 3, AcrySof MA60BM (Alcon Laboratories Inc, Fort Worth, Tex). All IOLs had a biconvex optical design, but they differed in the materials from which they were made: group 1, PMMA; group 2, silicone; and group 3, an acrylate/methacrylate copolymer. Ten phakic eyes of 7 patients who had neither systemic nor ocular complications, including cataract, underwent the same examination and served as controls (group 4).

The mean patient ages and the mean refractive powers of the implanted IOLs are presented in the Table. There were no significant differences among the 3 IOL groups. However, the mean age of the phakic group (group 4) was significantly lower than that of the other groups because patients with cataract were excluded from group 4. The Abbe number of the optical materials was obtained from the IOL manufacturers.

All patients underwent ocular examinations at least 1 month after surgery. They were evaluated for best-corrected distance visual acuity under white light. Contrast sensitivity was measured under white light and monochromatic light with wavelengths of 470 nm, 549 nm, and 630 nm, using a contrast vision tester modified from the MCT 8000 (Vistech Co, Dayton, Ohio), with the best correction under white light. In all cases, pupil size was about 3 mm. In group 4, to eliminate the effect of accommodation, all examinations were performed through a 3-mm-diameter artificial pupil placed in a trial frame and centered subjectively with respect to the subject’s pupil after the administration of cycloplegics.

The main components of the modified contrast vision tester are shown in Figure 1. The target for distance vision was presented under white light or monochromatic light (wavelengths, 470 nm, 549 nm, and 630 nm, each with 20-nm bandwidths) with the same luminance of 18 candela/square meter adjusted by an external light source (MegaLight 100; Hoya-Schott Inc, Tokyo) and neutral density filter (Fuji Filter ND 0.6; Fuji Photo Film Co, Tokyo).

We also distributed a questionnaire to patients to determine whether they had disturbances in color perception in their daily lives. Data analysis was performed using Statview (Abacus Concepts Inc, Berkeley, Calif). The mean age and the mean refractive power of the implanted IOLs were compared using 1-factor analysis of variance (ANOVA) and the Fisher protected least significant difference (PLSD) test. The best-corrected visual acuities and contrast sensitivities were analyzed using ANOVA and the Fisher PLSD test after converting the logarithmic values.

RESULTS

In all cases, the best-corrected visual acuity was 20/20 or better. The mean best-corrected visual acuity levels were 20/17 in all groups, and no significant differences were found among the groups (P > 0.05). The range of the refractive power for best correction was −4.5 to +1.5 diopters (D) in sphere and 0 to −2.25 D in cylinder. The mean contrast sensitivity levels are shown in Figures 2, 3, 4, and 5. There were no significant differences in contrast sensitivity among the 3 IOL groups (groups 1 to 3) at any spatial frequency under the 549-nm monochromatic light (Figure 4). However, under the white light and the 470-nm and 630-nm monochromatic light, the mean contrast sensitivity in group 3 tended to be lower than in groups 1 and 2, and there were significant differences at some spatial frequencies (Figures 2, 3, and 5).

The mean contrast sensitivity in the control group (group 4) was significantly higher than in all IOL groups under all conditions. No patients reported disturbances in color perception in their daily lives.

COMMENT

Before reviewing the data, we considered that the mean age of the patients in group 4 was significantly lower than for the other groups. Because contrast sensitivity is affected by age,4 the mean contrast sensitivity of group 4 was naturally higher than that of other groups under all conditions. Therefore, the data from group 4 should be treated as a reference and cannot be compared statistically with those from the other groups. However, because there were no significant differences in the profiles of the other 3 groups, including mean age, mean refractive power of the implanted IOLs, pupil diameter, and complications, the data from these groups can be compared statistically according to the different models of implanted IOLs.

Our results showed no significant differences in mean best-corrected visual acuity, but there were significant differences in mean contrast sensitivity among the IOL groups (groups 1 to 3) under normal conditions (white light). In addition to the patients’ profiles, several factors (primarily the cornea, IOL, and corrective lenses) can affect the contrast sensitivity or modulation transfer function in the optical system of the pseudophakic eye. Spherical aberration, irregular and asymmetric monochromatic aberrations, chromatic aberration of these components, and inaccurate focus all influence the modulation transfer function of the eye.5,6

The main aberrations affecting visual function are spherical and chromatic. Spherical aberrations of the corrective lenses can be ignored because the powers of these lenses are small (within ±5 D) and do not differ among
cases. Spherical aberrations of IOLs can also be ignored because they are sufficiently small compared with the chromatic aberrations under the pupil diameter (approximately 3 mm)^9 of the patients in this study. Regarding corneal spherical and chromatic aberrations, the effect on the differences of the mean contrast sensitivity

<table>
<thead>
<tr>
<th>Group</th>
<th>Optical Material (Model) [Refractive Index/Abbe No.]</th>
<th>No. of Eyes</th>
<th>Mean ± SD Age, y (Range)</th>
<th>Mean ± SD IOL Power, D (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PMMA (811C) [1.49/58]</td>
<td>14</td>
<td>63.7 ± 13.4 (34-77)</td>
<td>20.7 ± 1.7 (18.5-24)</td>
</tr>
<tr>
<td>2</td>
<td>Silicone (AQ110NV) [1.413/56.7]</td>
<td>10</td>
<td>66.6 ± 5.0 (56-73)</td>
<td>21.8 ± 1.6 (18.0-24)</td>
</tr>
<tr>
<td>3</td>
<td>Acrylate/methacrylate copolymer (AcrySof MA60BM) [1.55/37]</td>
<td>27</td>
<td>68.5 ± 9.4 (51-79)</td>
<td>21.3 ± 1.6 (18.0-24)</td>
</tr>
<tr>
<td>4</td>
<td>Normal crystalline lens [1.41/50]</td>
<td>10</td>
<td>32.4 ± 6.0† (27-46)</td>
<td>...</td>
</tr>
</tbody>
</table>

The mean age of the patients in group 4 was significantly lower than that of the other groups (P < .001).

Figure 1. Schematic representation of the contrast sensitivity measurement system. Wavelengths for monochromatic light were 470 nm, 549 nm, and 630 nm.

Figure 2. Mean contrast sensitivity under white light. A single asterisk indicates that P < .05 when groups 2 and 3 were compared. A double asterisk indicates that P < .05 when groups 1 and 3 were compared.

Figure 3. Mean contrast sensitivity under the 470-nm monochromatic light. A single asterisk indicates that P < .05 when groups 2 and 3 were compared. A double asterisk indicates that P < .05 when groups 1 and 3 were compared.

Figure 4. Mean contrast sensitivity under 549-nm monochromatic light. There were no significant differences among the intraocular lens groups (groups 1 to 3) at any spatial frequency.

*ICL indicates intracocular lens; D, diopters; PMMA, polymethyl methacrylate; and ellipses, not applicable.
†The mean age of the patients in group 4 was significantly lower than that of the other groups (P < .001).
can be disregarded because the data from each group were averages of patients with the same profiles. As a result, the main factor that caused the difference in contrast sensitivity was the chromatic aberration of the IOLs.

Chromatic aberration can be divided into 3 primary types: (1) LCA; (2) chromatic difference of magnification (CDM); and (3) chromatic difference of position (CDP). Chromatic aberration exists in normal phakic eyes but seems to cause no major problem under normal conditions.

The LCA is higher than 2 D across the visible spectrum in normal phakic eyes. In clinical terms, 2 D of uncorrected refractive error causes a serious visual handicap. However, previous reports showed that the effect of LCA on visual performance is not a major problem either theoretically or experimentally. If the individual accommodates to focus a wavelength in the middle of the spectrum, the range of refractive error is effectively halved to ±1.0 D. Because the extremes of the visible spectrum have less luminosity, the greatest amount of defocus is produced by those wavelengths that are least visible. Moreover, in clinical cases, such large LCAs do not become a major problem because chromatic blur is always masked by the luminance component.

According to a previous report, when the peak of the luminance spectrum is in focus, most of the light is less than 0.25 D out of focus. Therefore, when all the images of different wavelengths are superimposed on the retina, the visibility of the target is dominated by wavelengths that are only slightly defocused. Campbell and Gubisch also reported less than a 0.2-log-unit difference in contrast sensitivity for white and monochromatic lights across a 10 to 40 cycles per degree (cpd) range of spatial frequencies. The fact that we usually do not feel the effect of LCA supports these studies.

In pseudophakic eyes, the situation is different. The calculated LCAs of pseudophakic eyes were reported to be 0.64 D with a PMMA IOL, 0.98 D with an AcrySof IOL, and 0.74 D in the normal phakic eye (the Gullstrand thematic eye) between the wavelengths of 500 nm and 640 nm.

The calculated LCA of an eye implanted with an AcrySof lens is greater than that of the normal eye because the Abbe number of AcrySof is smaller than that of the normal eye. Because there is no accommodation in a pseudophakic eye, the LCA might affect visual function, especially in a pseudophakic eye with an IOL that has a small Abbe number. Our results seem to support this hypothesis.

Our results showed that contrast sensitivity was not significantly different among the 3 IOL groups at 549 nm. However, at other wavelengths, the contrast sensitivity of group 3 (AcrySof) tended to be lower than that of the other groups, and there were significant differences at some spatial frequencies. In this study, refractions were typically performed with broad-spectrum white lights, which possibly have luminance centroids near 555 nm.

Humans tend to adjust their accommodation to minimize blur irrespective of stimulus wavelength, so they are likely to accommodate to a wavelength near 555 nm when viewing a white stimulus. Because the 549-nm wavelength was used for one measurement and is close to 555 nm, the refraction under the 549-nm monochromatic light might approximate the best correction in all groups. Therefore, contrast sensitivity at 549 nm was not significantly different in the 3 groups. However, the contrast sensitivity in group 3 (AcrySof) was significantly lower than that of the other IOL groups in 470- and 630-nm light because the LCA of group 3 was greater than that of the other 2 groups. Our results support the hypothesis that defocusing by the larger chromatic aberration is a major factor causing degradation of contrast sensitivity in a pseudophakic eye with an IOL that has a small Abbe number.

Reportedly, when limiting the discussion to relatively low spatial frequencies (3 cpd) and moderate pupil sizes (3 mm), diffraction, off-axis imagery (angle α), transverse chromatic aberration, and even spherical aberration have a minimal effect on contrast, and the principal cause of retinal blur is LCA. Sensitivity to the effects of LCA is prominent at 3 cpd. These studies support our results that the effect of LCA on the mean contrast sensitivity may be most apparent at 3 cpd.

Chromatic difference of magnification is such a small change in angular magnification that it is generally thought to be insignificant for vision, and has been measured only experimentally. Its effects appear minor when compared with those of LCA; in our results, the effect of the transverse aberration seems less important. However, because the magnitude of the effect depends on the axial distance from the entrance pupil to the nodal point, CDM becomes an increasingly important factor when looking through an artificial pupil or any optical or clinical instrument, which moves the limiting aperture outside the eye. In the pseudophakic eye with an AcrySof IOL, visual function might be affected by CDM when using an artificial pupil such as a microscope.

The effect of CDP depends on the angle of incidence of the ray bundle or chief ray, which depends in
turn on the transverse position of the pupil and the eccentricity of the object.\textsuperscript{20} Wavelength differences in image position for fixated targets depend on the relative position of the pupil and visual axis. Because the natural pupil of the normal eye is well centered on the visual axis, foveal CDP is typically less than 1 minute of arc across the entire spectrum. However, CDP is not this small in eyes with decentered pupils and can exceed 25 minutes of arc between 400 and 700 nm if the pupil is displaced by 4 mm, even in phakic eyes.\textsuperscript{10} In pseudophakic eyes implanted with IOLs with a small Abbe number, if the postoperative pupil is eccentric, the CDP can affect visual function more than in phakic eyes.

The results from the questionnaires indicated that patients did not perceive a disturbance of color perception in their daily lives. However, Nagata et al\textsuperscript{14} reported the potential for a color vision disturbance caused by LCA under low luminance. If we use an IOL with a small Abbe number, such as AcrySof, the color perception might be affected by LCA under special conditions such as low luminance. Although the biocompatibility, manufacturing, and maneuverability of new IOL materials have been previously studied, our results indicate that the LCA of some IOLs may degrade the retinal image quality under special conditions. We must give attention to the detailed optical performance of the material to achieve optimum visual function after IOL implantation.

Accepted for publication January 10, 2001.

This study was supported by Health Sciences Research Grant 12120204 from the Ministry of Health and Welfare, Tokyo, Japan.


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