Effects of Intraocular Lens Opacification on Light Scatter, Stray Light, and Overall Optical Quality/Performance

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Cataract surgery is the most prevalent operation in the United States, with more than 3 million procedures performed in 2006 alone.1 A variety of new artificial intraocular lens (IOL) designs, manufactured from different biomaterials, are continuously being made available to cataract surgeons to replace the refractive power of the surgically-removed opacified crystalline lens. The biomaterials used in IOL manufacture are basically divided into two main classes: acrylic (rigid and foldable) and silicone (foldable). Although relatively rare, explantation of an IOL may be required due to problems such as error in IOL power calculation, postoperative inflammation, and postoperative opacification of the IOL, among others.2 Postoperative calcification represents the most important indication for explantation of hydrophilic acrylic IOLs.2–7 Silicone lenses were also shown to calcify in eyes with asteroid hyalosis.8–10 The condition named snowflake degeneration of rigid polymethylmethacrylate (PMMA) lenses still leads to explantation of a significant number of these IOLs, although it is usually observed in three-piece lenses manufactured in the 80s and early 90s.11,12 Calcification and snowflake degeneration appear to be predominantly related to increased forward light scattering and subsequently retinal stray light, which can give rise to a variety of subjective complaints, including glare in various illuminating conditions, halos around bright lights, color and contrast loss, as well as hazy vision.13 These symptoms may prompt IOL explantation even in the absence of measurable decrease in visual acuity.13–15

In previous studies, we evaluated light scattering and light transmission in IOLs explanted because of clinically significant postoperative opacification.16,17 Very high levels of light scattering and a potential for decrease in light transmission were found. However, only back scattered light was measured with a Scheimpflug camera (dispersion of light reflected out of the eye that can be seen by an external observer). More recently, a technique developed for measuring the forward light scattering (light toward the retina) of IOLs in vitro was described.18 Through specific mathematical relationships, forward light scattering can be converted to a more clinically relevant metric to determine the potential impact of optic opacification on visual performance, the stray light.18 Therefore, the aim of the current study was to provide a complete characterization of the effects of IOL opacification on the visual function, by measuring forward light scattering and stray light, as well as other optical quality/performance indicators.
Effects of IOL Opacification on Stray Light

**TABLE 1. Explanted and Control Intraocular Lenses Included in the Study**

<table>
<thead>
<tr>
<th>Hydrophilic Acrylic, N = 13</th>
<th>Hydrophilic Acrylic Control, N = 5</th>
<th>Silicone</th>
<th>Silicone Control</th>
<th>PMMA, N = 4*</th>
<th>PMMA Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ioflex, N = 4</td>
<td>Ioflex, N = 2</td>
<td>Chiroflex C10UB, N = 1</td>
<td>Chiroflex C10UB, N = 1</td>
<td>UVL-304-01, N = 2</td>
<td>809A, N = 1</td>
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<td>Centerflex, N = 2</td>
<td>Aqua Sense, N = 1</td>
<td>Unknown model, N = 2</td>
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<td></td>
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<tr>
<td>Hydroview, N = 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MemoryLens, N = 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* All explanted PMMA lenses were 3-piece designs with Prolene loops, implanted in the late 80s and early 90s.

**MATERIALS AND METHODS**

Intraocular lenses explanted because of optic opacification associated with significant decrease in the visual function, with symptoms of glare and cloudy vision, and sent to the John A. Moran Eye Center at the University of Utah (Salt Lake City, Utah, USA) for evaluation were used in this study. All lenses underwent gross and light microscopy. In order to remove surface crystals corresponding to dry ophthalmic viscosurgical device (OVD) and/or balanced salt solution (BSS) used during the explantation procedure, the IOLs were rinsed with distilled water and allowed to dry at room temperature before re-evaluation under gross and light microscopy. Because the IOLs needed to be fixed inside special supports for the various measurements, only IOLs explanted without major deformation of the haptic components could be used. The following groups of IOLs were included:

1) Single-piece or three-piece hydrophilic acrylic lenses, explanted because of calcification (N = 13);
2) Single-piece plate silicone lens, explanted because of calcification in an eye with asteroid hyalosis (N = 1); and
3) Three-piece PMMA lenses, explanted because of snowflake degeneration (N = 4).

Never implanted hydrophilic acrylic, silicone plate, and PMMA lenses were used as controls (5 hydrophilic acrylic lenses, 1 silicone, and 1 PMMA lens). Table 1 provides information on the models of explanted and control IOLs used in this study. Regarding the explanted calcified hydrophilic acrylic lenses, the water content of their materials is as follows: 25% (Ioflex; Mediphacos, Belo Horizonte, Brazil, and Aqua Sense; Aaron Scientific, Ontario, CA, USA), 26% (PolyLens; Tekia, Irvine, CA, USA, and Centerflex; Rayner, Hove, UK), 18% (Hydroview; Bausch & Lomb, Rochester, NY, USA), and 20% (MemoryLens; CibaVision, Duluth, GA, USA). None of the hydrophilic acrylic lenses included has a hydrophobic coating/surface modification.

Forward Light Scattering

Measurements were performed with the Complete Angle Scattering Instrument (CASI) scatterometer. This instrument uses a laser source of 633 nm to illuminate BSS-immersed IOLs within a cylindrical wet cell. The wet cell was placed at the center of rotation of a goniometer arm. A detector measured light scattered per unit solid angle from the IOL as a function of angle. The measurements provided a profile of the scatter distribution for regions outside of the directly transmitted beam represented as the bidirectional scattered distribution function (BSDF). Scattering results were then converted to a more clinically relevant metric to determine the potential impact of optic opacification on visual performance (stray light values). Details on the measurement of forward scattering by using this device, as well as the conversion of measured values into stray light values have been recently described.

Modulation Transfer Function and Badal Images

Modulation transfer is the ability of a lens or optical system to transfer an object’s contrast to its image. Modulation transfer function (MTF) of the lenses was obtained in the hydrated state using an optical bench and a model eye. The model eye imaged an illuminated slit and the MTF was proportional to the modulus of the Fourier transform of the slit image. The MTF values were obtained using 3- and 5-mm pupils. Badal images were also obtained using a letter chart object with the same pupil sizes.

Back Light Scattering and Light Transmittance

In order to confirm results from previous studies, back scattering and light transmittance were measured. A customized three-piece dark eye model with a PMMA cornea was used to hold the IOLs under immersion in BSS. Care was taken to prevent the presence of air bubbles inside of the eye model during loading and assembly. The BSS-filled model containing the IOL was then placed in front of a Nidek (Gamagori, Japan) EAS-1000 Scheimpflug camera (cornea facing the device), and the room lights were turned off. A cross-sectional image of the IOL inside of the model was then obtained (settings: flash levels 200 W and 50 W; slit length 10 mm; meridian angle 0) and analyzed using the densitometry peak function. Light scattering values were expressed in computer compatible tape (CCT). This is a measure of brightness or intensity of reflected (scattered) light.

According to the operator’s manual, the raw pixel density level of the device ranges from 0 to 255 without background correction. Measurements of light transmittance were performed with a Lambda 35 UV/Vis spectrophotometer, equipped with a Lab Sphere RSA-PE-20 integrating sphere with a 50-mm diameter (Perkin-Elmer, Waltham, MA, USA) operated in a single beam configuration. Each IOL was fitted to a plastic custom insert with a 5.0-mm diameter aperture for the optic (designed to hold a 6.0-mm diameter optic). The insert containing the IOL was then mounted into a standard rectangular quartz cuvette filled with BSS. Care was taken to prevent the presence of air bubbles inside the cuvette. The assembly was then placed directly in front of the opening of the integrating sphere so that the anterior surface of the IOL was facing the light source. Prior to the measurements, a background correction was performed with the empty inserter immersed in BSS inside the quartz cuvette. Background transmittance spectra were checked to ensure that 100 ± 0.5% transmittance was achieved. Intraocular lens spectra were then collected at room temperature with the following settings: wavelength range 300
to 850 nm; slit width 2 nm; scan speed 120 nm/min; data interval 1 nm. At least two measurements were recorded for each IOL and averaged; background transmittance was checked every other sample to ensure that it did not shift during measurements. Results were expressed as percent light transmittance (%T) in the visible light spectrum (400–700 nm).16,17

RESULTS

Figure 1 shows representative gross photographs of the lenses explanted because of clinically significant optic opacification. Gross and light microscopy of the explanted hydrophilic acrylic lenses showed calcified deposits, which were predominantly located within the optic substance \((N = 9)\) or on the surface/subsurface of the lenses \((N = 4)\). The single-piece, plate silicone lens with large positioning holes exhibited a dense central area of calcified deposits located on the posterior optic surface only. Gross and light microscopy of the explanted PMMA lenses confirmed the presence of typical intraoptic snowflake lesions. They were usually confined to the most central part of the optic, leaving a clear peripheral edge devoid of lesions.

Forward Light Scattering

The plots in Figures 2 through 4 display the forward light scattering of representative lenses from the three different groups. Details on the stray light values, calculated from the measured forward light scattering values are presented in Table 2. Forward light scattering and stray light values from lenses explanted because of calcification and snowflake degeneration were considerably higher than the values for the corresponding controls. Comparison of stray light values between explanted opacified lenses \((N = 18)\) and controls \((N = 7)\) was statistically significant for all angles analyzed (two-tail \(P < 0.001\) at 10°, \(t\)-test; 95% confidence interval for the mean difference 1.08–1.68).

Modulation Transfer Function and Badal Images

Modulation transfer function and Badal image contrast were found to be reduced for all explanted lenses with calcification and snowflake degeneration. Figure 5 shows the MTF graphs of a representative lens from the calcified hydrophilic acrylic group with corresponding control. Figure 6 shows Badal images obtained from a representative PMMA lens with snowflake degeneration and corresponding control.

Back Scattered Light

Figure 7 shows Scheimpflug photographs with densitometry measurements of representative explanted lenses from each of the three groups. Eight of 18 explanted opacified lenses (44%) had saturated peak density measurements, as values were greater than or equal to 200 CCT at both the highest (200 W) and lowest (50 W) flash settings. In contrast, 100% of the control samples were less than or equal to 9 CCT at the highest (200 W) flash setting. The percent incidence of explanted opacified lenses with CCT greater than or equal to 200 was compared with the controls using Fisher’s exact test. Two-tailed \(P\) value was less than 0.001 at 200 W.

Light Transmittance

The average light transmittance (T) in the visible light spectrum for all 13 calcified hydrophilic acrylic lenses was 87.38 ± 4.85%. The mean value obtained for the control hydrophilic acrylic
FIGURE 2. Graphs comparing forward light scattering from four representative explanted hydrophilic acrylic lenses exhibiting calcium deposits predominantly within the optic substance, and two control lenses of the same design. PSF, point spread function.

TABLE 2. Stray Light Values (Log (s)) for Explanted Hydrophilic Acrylic, Silicone, and PMMA Lenses Calculated From Forward Light Scattering Measurements Obtained at Various Angles.

<table>
<thead>
<tr>
<th>Angle, Deg</th>
<th>Hydrophilic Acrylic, N = 13</th>
<th>Hydrophilic Acrylic Controls, N = 5</th>
<th>Silicone, N = 1</th>
<th>Silicone Control</th>
<th>PMMA, N = 4</th>
<th>PMMA Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.57 ± 0.34</td>
<td>0.64 ± 0.10</td>
<td>1.63</td>
<td>0.73</td>
<td>1.57 ± 0.35</td>
<td>0.61</td>
</tr>
<tr>
<td>10</td>
<td>1.79 ± 0.37</td>
<td>0.36 ± 0.05</td>
<td>1.53</td>
<td>0.41</td>
<td>1.62 ± 0.46</td>
<td>0.25</td>
</tr>
<tr>
<td>15</td>
<td>1.82 ± 0.34</td>
<td>0.22 ± 0.06</td>
<td>1.47</td>
<td>0.30</td>
<td>1.63 ± 0.47</td>
<td>0.13</td>
</tr>
<tr>
<td>20</td>
<td>1.81 ± 0.30</td>
<td>0.15 ± 0.02</td>
<td>1.41</td>
<td>0.24</td>
<td>1.60 ± 0.49</td>
<td>0.03</td>
</tr>
<tr>
<td>25</td>
<td>1.77 ± 0.27</td>
<td>0.14 ± 0.04</td>
<td>1.39</td>
<td>0.16</td>
<td>1.58 ± 0.50</td>
<td>−0.07</td>
</tr>
<tr>
<td>30</td>
<td>1.70 ± 0.27</td>
<td>0.12 ± 0.06</td>
<td>1.36</td>
<td>0.21</td>
<td>1.55 ± 0.51</td>
<td>−0.16</td>
</tr>
</tbody>
</table>

FIGURE 3. Graphs comparing forward light scattering from one explanted calcified silicone lens, and a control lens of the same design.
lenses was $97.87 \pm 0.70\%$. The %T for the silicone plate lens explanted because of calcification in an eye with asteroid hyalosis was $94.6\%$; it was $97.7\%$ for the never implanted control silicone lens. The %T for the PMMA lenses exhibiting snowflake degeneration was $88.9 \pm 3.7\%$. The value obtained for the never implanted control PMMA lens was $98.8\%$.

**DISCUSSION**

Calcification (hydrophilic acrylic and silicone IOLs), and snowflake degeneration (PMMA IOLs) usually lead to progressive opacification of the IOL optic, resulting in significant decrease of the visual function requiring explantation/exchange of the affected lens.\(^3\) Calcification of hydrophilic acrylic lenses appears to be a multifactorial problem, and factors related to IOL manufacture, IOL packaging, surgical techniques and adjuvants, as well as patient metabolic conditions, among others may be implicated. As the exact combination of factors and sequence of events ultimately leading to calcification of the lenses is still unknown, continuous research on this complication is warranted.\(^3\) The majority of the studies on calcified hydrophilic acrylic lenses describe explantation during the second postoperative year, or earlier. In some cases, the deposits causing the opacification are found on the optical surface/subsurface of the lenses, while they are predominantly found within the optic substance in others.\(^4-7\) In cases of calcification of silicone lenses in eyes with asteroid hyalosis, studies demonstrated deposits only on the posterior optic surface of the lenses. The deposits could be partially removed with Nd:YAG laser, but there was a reaccumulation after the procedure because the asteroid bodies are rich in calcium/phosphate.\(^8-10\) Snowflake degeneration is a slowly progressive condition; it is the result of PMMA degradation caused by long-term ultraviolet light exposure, not calcium deposition. The degree of optic opacification of the majority of the PMMA lenses included in this study may take 10 to 20 years to develop. The intraoptic spherical lesions observed in these cases are thought to correspond to sites of degenerated PMMA material.\(^11,12\)

We have already performed two preliminary studies evaluating back scattered light and light transmittance in IOLs explanted because of clinically significant optic opacification.\(^16,17\) In both studies, the same Scheimpflug and spectrophotometer devices described in our current study were used. The first study included various designs of hydrophilic acrylic lenses with different patterns of calcification, as well as a silicone lens explanted because of calcification on the
posterior optic surface in an eye with asteroid hyalosis, and PMMA lenses with snowflake degeneration. Back scattered light in that series was extremely high, with 26 of 31 explanted lenses measured between 205 and 227 CCT. On average, the percentage of light transmittance in that same study was reduced by 8.43% in hydrophilic acrylic IOLs with calcification, 3% in the calcified silicone lens, and 9.53% in the PMMA IOLs with snowflake degeneration. In the second study, seven explanted calcified hydrophilic acrylic lenses and eight control lenses of the same design were studied. Back light scattering was $219.71 \pm 2.62$ CCT for explanted IOLs, and $4.75 \pm 2.50$ CCT for controls IOLs. The average light transmittance in the visible light spectrum was 75.94% to 87.25% for explanted IOLs, and 97.54% to 98.97% for control IOLs.

The fact that the earlier publications included only the measurements of back light scattering was a major limitation of those studies. The forward light scattering measurements and subsequently the stray light would provide a meaningful correlation with possible clinical symptoms related to glare disability and stray light hindrance. Therefore, in the current study forward light scatter, stray light, and other optical quality/performance indicators were also assessed for lenses explanted because of clinically significant opacification. Both the back and forward light scattering were significantly increased in the explanted lenses, which resulted in the reduction of light transmission, MTF, and Badal image contrast for the opacified lenses.

Different studies demonstrated that stray light increases with age in the healthy eye. Under 40 years of age, a normal stray light value ($\log (s)$) is 0.9 ($s \approx 8$). This value increases to $\log (s) = 1.2$ ($s \approx 16$) at age 65, which corresponds to double the amount of stray light in a 40-year-old eye. On average, stray light remains relatively unchanged at up to 40 years of age. It doubles in noncataractous eyes by the age of 65 years and triples by the age of 77 years as compared with the young eye. Therefore, the older crystalline lens is an important source of stray light, even if it is clear. Any disturbances of the optic media (e.g., cataracts) will further increase the stray light with age. Phacoemulsification with IOL implantation has the potential to revert the increase in stray light related to cataracts, as well as age. A prospective observational case series objectively compared the mean level of intraocular stray light 6 months postoperatively in patients implanted with a multifocal or a monofocal posterior chamber IOL. The study found that cataract surgery lowered the mean level of intraocular stray light compared with the level in age-matched noncataractous subjects. Also, the amount of light scatter from different IOLs measured in vitro was typically lower than that found in healthy donor crystalline lenses of various ages. van den Berg et al. described the impact of stray light in human vision, with serious hindrance found above 1.47 $\log (s)$. 

**Figure 6.** Badal images of a PMMA lens explanted because of snowflake degeneration (A, C), as well as a control PMMA lens (B, D), measured at 3.0- (A, B) and 5.0- (C, D) mm pupils.
FIGURE 7. Scheimplug photographs with densitometry analyses of a representative lens from each of the three groups (same lenses as in Fig. 1). (A) Calcified single-piece hydrophilic acrylic lens; backward light scattering was measured as 222 CCT. (B) Calcified single-piece plate silicone lens, removed from an eye with asteroid hyalosis. Backward scattering = 223 CCT. (C) Three-piece PMMA lens with snowflake degeneration. Backward scattering = 225 CCT (image obtained with a flash level of 50 W).
cause a serious negative impact on the visual function, even if visual acuity was not significantly reduced.

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**References**


