Retinal stray light originating from intraocular lenses and its effect on visual performance
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Chapter 7

Impact of intraocular lens material and design on light scatter: In vitro study

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PURPOSE:
To determine the typical in vitro straylight levels for intraocular lenses (IOLs) of different materials and designs.

SETTING:
Abbott Medical Optics, Inc., Groningen, the Netherlands.

DESIGN:
Experimental study.

METHODS:
Two optical bench setups were used to determine baseline straylight levels of IOLs placed in a saline-filled cuvette: one for forward scatter positions between 0.6 and 3.0 degrees and one for positions up to 22.0 degrees. Line-spread functions were measured using the small angle setup, and scattered light intensity was measured using the wide-angle setup. From these measurements, the angular dependent straylight parameter was calculated. Ten IOLs of different materials (hydrophobic and hydrophilic) and designs (monofocal or diffractive multifocal and spheric or aspheric) were studied, and their measured straylight levels were compared with the levels in a 20-year-old and a 70-year-old healthy noncataractous human crystalline lens.

RESULTS:
Irrespective of the material or design, monofocal IOLs had straylight levels below or close to those of a 20-year-old human crystalline lens. Diffractive multifocal IOLs had straylight levels higher than those of monofocal IOLs but less than those of a 70-year-old human crystalline lens. With increasing angle, hydrophobic IOLs showed a gradual decrease in straylight level. After an initial decrease, hydrophilic IOLs showed an increase in straylight level for larger angles.

CONCLUSIONS:
The baseline straylight levels of IOLs were design and material dependent (hydrophobic < hydrophilic; monofocal < diffractive multifocal). Most monofocal IOLs had straylight levels below the levels in a 20-year-old human crystalline lens.
Imperfections in ocular media cause light entering the eye to be scattered. Natural imperfections can be irregularities that occur at the interface of ocular media (e.g., cornea to aqueous) or particles, such as proteins, that are present in the medium. This causes part of the light, initially directed toward the focus point on the retina, to disperse onto the surrounding retina. Consequently, less light will reach the focal point on the retina. The scattered light, or straylight, thus diminishes the contrast of the optical image formed.\textsuperscript{1,2} The natural crystalline lens also contributes to the scattering of light. In young crystalline lenses, the amount of scatter is minimal, but as the natural lens ages, the amount of straylight originating from the crystalline lens increases because of the natural aging process of the lens.\textsuperscript{3–6} The increased straylight causes visual symptoms such as disability glare during night driving and hindrance from low sun during daytime.\textsuperscript{2} Cloudy lenses or cataracts are the extreme of the aging process; light passing through a cataractous lens is more scattered, resulting in a significant loss of contrast.\textsuperscript{7} Even though straylight may cause as much functional vision loss as visual acuity and the impact of light scattering from cataracts is well understood, current clinical assessment for cataract surgery is primarily based on visual acuity measurements and slitlamp examination of the density of the crystalline lens. Retinal straylight from light scattering due to cataracts may, however, case as much functional vision loss as poor visual acuity.\textsuperscript{5,8–11} Additionally, retinal straylight and visual acuity behave independently.\textsuperscript{1,5–7,9,12} Therefore, several clinical investigators have advocated the use of an increase in straylight as an indication for cataract surgery.\textsuperscript{2,5,8–11} Previous in vivo measurements using the C-Quant straylight meter (Oculus Optikgeräte GmbH) show that pseudophakic eyes have straylight levels comparable to or below that of healthy eyes.\textsuperscript{5} This finding demonstrates that the cataract is the largest source of intraocular light scatter and that its extraction and replacement with an intraocular lens (IOL) lowers the amount of straylight and the related visual effects. Commercially available IOLs differ in their material, design, and manufacturing method, all of which are potential sources of light scatter;\textsuperscript{5,13} however, the extent to which they introduce straylight and how that relates to typical straylight levels in healthy young and old eyes have not been well defined. Increased knowledge of the straylight introduced by different types of IOLs would contribute to a broader and better understanding of the visual consequences of IOL designs and materials. This knowledge would also help in managing patient expectations, which is especially important given the increased attention to light scatter and its role in functional vision loss. In this study, in vitro measurements were performed to determine the baseline straylight levels for IOLs differing in design, material, and/or manufacturing method. The obtained results were compared between individual types of IOLs as well as with the straylight levels published for 20-year-old and 70-year-old healthy crystalline lenses.\textsuperscript{13}
MATERIALS AND METHODS

The straylight levels of 10 types of IOLs were studied. Only sterile IOLs were used. The IOLs were made from 4 acrylic materials labeled as hydrophobic and 2 acrylic materials labeled as hydrophilic. They had 4 optical designs: spheric or aspheric and monofocal or diffractive multifocal. Table 1 summarizes the details of the IOLs and the nomenclature used to address them in this article (acrylic A to F). The IOLs' straylight was measured in 2 laboratory-based setups, together covering an angular domain from the optical axis up to 22 degrees. A short overview of both setups is given below. A more detailed description of the measurements and their background has been given by van der Mooren et al. 13

Straylight

The straylight parameter $s(q)$ introduced by van der Berg 4 allows quantification of the amount of straylight, both in vivo and in vitro. By definition, the straylight parameter is the equivalent luminance divided by the illuminance of the glare source falling into the eye x angle square. 16 The straylight corresponds to the skirts of the point-spread function (PSF) as presented in equation 1. 16

$$s(\theta) = \frac{\text{PSF}(\theta) \times \theta^2}{\text{sr}} \text{ [degrees}^2/\text{sr]}.$$  \hspace{1cm} (1)

Setup 1: Small Angle (up to 3.0 Degrees)

The first setup, to measure scatter for small angles, is shown in Figure 1. 13 After being hydrated in saline for at least 24 hours, the IOLs were placed in a saline-filled cuvette and
placed on an optical bench in an eye model that reproduces the spherical (c [4.0] = 0.27 mm) and chromatic (0.4 mm between hydrogen F and C lines) aberration of an average pseudophakic eye\textsuperscript{17,18} using white light and a 4.0 mm aperture. A 3.0 mm slit, corresponding to 0.5 degree, was used to collect information on the outer skirts of the PSF.\textsuperscript{13} The light intensity distribution of each IOL was obtained using a stepwise lateral displacement of the charge coupled device (CCD) camera, which captured the linespread function. Using 5 steps, an intensity range of 6 orders of magnitude over an angle of ±3 degrees with respect to the optical axis was obtained (Figure 2). For each position, a different shutter time was applied to cover the maximum light intensity range for that particular position. The PSF was obtained by integrating the line-spread function along the image slit. The angular position was calculated from the pixel position, the magnification, and the nodal point. From the PSF and the angular positions, the angular dependent straylight parameters, s(θ), for forward scatter positions between 0.6 and 3.0 degrees were calculated using equation 1.\textsuperscript{13,16}

Figure 2. Five line-spread function measurements represented by 5 colors were stitched together to obtain the line-spread function over the entire angular range. The lateral displacement of the CCD with respect to the central optical axis is denoted in the legend for each line-spread function recording.
Figure 3. Wide-angle measurement setup.

Setup 2: Wide Angle (up to 22.0 Degrees)

The wide-angle setup is shown in Figure 3. After the IOLs were hydrated in saline for at least 24 hours, the straylight was measured by placing the IOLs in a saline-filled cuvette. A light source was defined and directed using several lenses and filters. The intensity of the light transmitted by the IOL was measured using a CCD camera at different angles relative to the incident beam. The CCD camera and the cuvette were shielded by a black curtain. Similar to the small-angle setup, the camera’s shutter times were increased with increasing measurement angle to detect the decreasing light intensity. All analyses were performed using a 4.0 mm aperture. The PSF was calculated from the measured light intensities, light power $P(\theta)$, using equation 2, in which $\Omega$ represents the solid angle and $P_0$ is the total light transmitted by the IOL.

$$PSF(\theta) = P(\theta) / (\Omega \times P_0)$$

Subsequently, the straylight parameter $s(\theta)$ was calculated from the PSF and the forward scatter angle using equation 1.

Data Analysis

The straylight levels for the IOL designs and materials were compared with each other and with the published levels for healthy noncataractous 20- and 70-year-old human crystalline lenses. By definition, the setup measures the tail of the line-spread function; however, the straylight parameter $s(\theta)$ is calculated from the PSF. Because in the small-angle method the linespread function approximates the PSF for angles greater than 0.5 degree, results are presented for 0.6 degree outward. For angles smaller than 0.6 degree, no valid PSF values could be measured because of the use of a 0.5 degree slit target. For
both measurement setups, the measurements were considered to be symmetrical around the optical axis. Therefore, the results from the negative and positive angles were averaged. The results from the small-angle and wide-angle measurements were combined for each IOL. One IOL was measured for each model listed in Table 1. For 4 IOL models, straylight from at least 2 different IOLs was measured. For each of the IOL models, the maximum standard deviation was 5% of the mean straylight values for the complete angular range. Based on this outcome, it was considered reasonable to use the measurements on 1 IOL for each model as a representable baseline.

### RESULTS

#### Material Comparison

The straylight levels for the 4 monofocal aspheric IOLs made from materials labeled as hydrophobic acrylic were well below those of the straylight levels of a 20-year-old human crystalline lens. For small forward scatter angles in the range of 0.6 to 3.0 degrees, straylight levels of the IOLs were similar to each other and decreased with increasing angle (Figure 4). For larger angles, the curve representing the straylight levels for acrylics A and B tended to flatten out; however, the curves for acrylics C and D showed a small increase in straylight levels as the forward scatter angle increased from 4 to 20 degrees. In Figure 5, the straylight levels for IOLs made from materials labeled as hydrophilic acrylic are presented. For small forward light scatter angles (up to 3.0 degrees), straylight levels were well below the levels of a 20-year-old human crystalline lens. For angles larger than 3.0 degrees, the straylight levels increased, reaching that of a 20-year-old human crystalline lens at forward scatter angles of approximately 20.0 degrees.
Figure 4. Material comparison between monofocal aspheric IOLs made from 4 different hydrophobic acrylic materials (acrylicA to D).

Figure 5. Material comparison between monofocal aspheric IOLs made from 2 different hydrophilic materials (acrylics E and F).
Design Comparison

To determine whether design-related differences influenced straylight, 1 spheric and 1 aspheric monofocal IOL made from hydrophobic acrylcs A and B were compared (Figure 6). All the spheric and aspheric monofocal IOLs showed decreasing straylight levels for the small forward scatter angles, with the overall levels remaining well below those of a 20-year-old human crystalline lens. In general, the aspheric monofocal IOLs had slightly lower straylight levels than the spheric monofocal IOLs. Figure 7 compares the straylight levels for monofocal and diffractive multifocal IOLs made from hydrophobic acrylcs. Both diffractive multifocal IOLs had a 4.0 diopter addition power. Straylight levels for diffractive multifocal IOLs were higher than those for monofocal IOLs but remained below those of a 70-year-old human crystalline lens. Additionally, for scatter angles greater than 2.0 degrees (aspheric design) or 7.5 degrees (spheric design), straylight levels of diffractive multifocal IOLs decreased to levels below those of a 20-year-old human crystalline lens and flattened out with larger angles.

Figure 6. Design comparison of 1 spheric and 1 aspheric monofocal IOL made from acrylcs A and B.
Figure 7. Design comparison of IOLs made from (a) acrylic A having a monofocal aspheric and a diffractive multifocal aspheric design (top) and (b) acrylic B having a monofocal spheric and a diffractive multifocal spheric design (bottom).
DISCUSSION

Intraocular lenses were measured in an ideal in vitro situation. The absolute and relative straylight levels measured should therefore be considered as a baseline situation. In vivo, the amount of straylight will be defined not only by the type of IOL, but also by the presence of other light-scattering interfaces such as the capsular bag, striae, and the presence of posterior and/or anterior capsule opacification. These biological aspects as well as material inhomogeneity may vary from person to person and may change over time. Monofocal IOLs had straylight levels below or close to the levels of a 20-year-old human crystalline lens, irrespective of the material or design (spheric or aspheric). Diffractive multifocal IOLs had relatively higher straylight levels, but the levels did not exceed those of a 70-year-old human crystalline lens, and with increasing angle, the levels dropped to less than those of a 20-year-old human crystalline lens. These larger forward scatter angles correspond to the region that is considered to be outside the region affected by the halo that results from a diffractive multifocal design. The differences in straylight levels between monofocal and diffractive multifocal IOL designs can be assigned to the straylight originating from the higher-order foci of the diffractive surface. Removing a cataractous lens and replacing it with an IOL is expected to lower the lens' contribution to straylight in the eye. This is consistent with the observations by van den Berg et al., who compared in vivo straylight levels before and after cataract surgery. Analysis of straylight levels at different forward scatter angles revealed that most of the hydrophobic acrylic IOLs showed a decrease in straylight levels with increasing forward scatter angles until they reached a plateau for the large angles (Figure 4). In contrast, for hydrophilic IOLs, the initial decrease in straylight levels for smaller angles was followed by a similar gradual increase for larger angles (Figure 5). A veil is apparent on the hydrophobic IOLs at large scatter angles; for example Figure 8 shows the photographs taken during the measurements for a hydrophobic and a hydrophilic acrylic IOL from the same manufacturer at a small (1.5 degrees) and a large (22.0 degrees) forward scatter angle. A veil is clearly seen on the hydrophilic IOL at 22.0 degrees forward scatter angle. Water content may also vary among the hydrophobic acrylic IOLs (Table 1). A review of Figures 4 and 5 shows a trend toward increasing straylight parameter values at scatter angles of 3.0 degrees onward for acrylic material C that is similar to that for hydrophilic IOLs. The absolute increase in the straylight parameter value for hydrophobic material C is not as large as that for the hydrophilic IOLs. Material C has the highest water content of all hydrophobic materials tested (Table 1) but not as high as the hydrophilic materials; this may point toward a relationship between the IOL materials' water content and the straylight parameter behavior for large forward scatter angles. Future work may focus on investigating possible mechanisms explaining this observation. In addition to IOL material and design, surface and bulk irregularities arising from the manufacturing process may influence the amount of straylight measured. In this study, IOLs from different
manufacturers were used and therefore the manufacturing process may have influenced the straylight levels observed. The eye model used for the small-angle measurements was designed to reproduce the average corneal spherical aberration. Straylight levels of spheric and aspheric IOLs measured in this study were low and their relative differences may not be attributed to spherical aberration because this factor is expected to play a role for angles that are much smaller than 0.6 degrees. The higher straylight values obtained from the small-angle setup measurements in the overlapping angular range for all IOLs except the multifocal spheric lens B (Figure 7) may be explained by a difference in the base straylight level of the measurement setups used in this study. Straylight measurements require the accurate determination of light intensities over a large range of values. In the low intensity regions, accurate straylight measurements become increasingly challenging. This may lead to variation in absolute straylight parameter values when the same IOL is measured under different conditions (eg, on another day) or when the same IOL model from a different manufacturing batch is measured. This is especially true for monofocal IOLs as they showed straylight levels close to the straylight levels of the setup without an IOL. Intraocular lenses were only measured when the straylight value for the setup alone was at least 0.5 log unit below the level of a healthy noncataractous 20-year-old human crystalline lens, as described by the in-depth explanation of this method by van der Mooren et al.\textsuperscript{13}

Additionally, a repeatability study has been performed on a monofocal and a multifocal IOL with 3 repetitions on each IOL. The maximum standard deviation was 13\% of the mean straylight values for the complete angular range. The results presented in this study can help predict the consequences of a change in IOL design, material, or manufacturing process on the postoperative straylight level in pseudophakic eyes. The baseline levels that we measured can be used to inform patients of the expected straylight level and possible improvement in visual effects. Future work may include in vivo measurements of aged IOLs and/or the comparison of the in vitro straylight levels presented in this paper with the straylight levels from in vivo measurements in pseudophakic eyes. In conclusion, this study found that most monofocal IOLs have straylight levels below the levels published for a healthy noncataractous 20-year-old human crystalline lens. Light scattering is influenced by IOL material and design; hydrophobic IOLs tend to have lower straylight levels than hydrophilic IOLs for scatter angles larger than 3.0 degrees and IOLs with a monofocal IOL design have lower straylight levels than IOLs having a diffractive multifocal design.
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Figure 8. Acrylic C (left) and acrylic E (right) monofocal IOLs taken in the wide-angle setup at a forward scatter angle of 1.5 degrees (top) and 22.0 degrees (bottom) (white light, in saline). A veil is clearly visible on the hydrophilic IOL at large angles (bottom right).

WHAT WAS KNOWN

- Intraocular light scatter due to cataracts is a known source of functional vision loss.
- Extraction of the cataractous lens and replacement with an IOL lowers the amount of straylight.

WHAT THIS PAPER ADDS

- In vitro straylight measurements of different IOLs show that baseline straylight levels depend on their design and material (monofocal < diffractive multifocal; hydrophobic < hydrophilic).
- Irrespective of the material, all monofocal IOLs show in vitro baseline straylight levels below the levels reported for a 20-year-old healthy human crystalline lens.
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Impact of intraocular lens material and design on light scatter: In vitro study


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