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Light scattering from a diffractive-refractive intraocular lens: a goniometer-based approach for individual zone assessment

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Abstract: We proposed and tested a method to measure light scattering from the diffractive lens profile in an echelle element featuring 9 zones. Measurements were performed using a goniometer-based setup up to 7.5°. The proportion of scattered light was calculated to derive the loss of light. Material scattering was minimal (~1 deg^2/sr); however, each echelle zone acted as a scattering source. A nearly gradual straylight increase was found with the zone number showing peak intensity between 3° and 3.75°. An estimated 6.2% ± 0.1% was lost due to scattering, which ought to be considered when reporting an IOL's light loss.

1. Introduction

Diffractive-refractive intraocular lenses (IOLs) were introduced to cataract surgery more than three decades ago [1]. Since then, various optical designs have evolved with a continuous effort to improve the visual quality and minimize associated photic phenomena [2]. Although glare complaints have often been ascribed to the simultaneous projection of two or more foci [3], the contribution of light scattering at diffractive gratings has also been expected to be important [2]. Indeed, the appearance of a diffractive-refractive IOL at a slit lamp directly points to light scattering taking place: the edges between the zones show up because of the redirection of light [2]. It must be expected that also for the patient's vision, this light scattering takes place, leading to the visual phenomenon of straylight. The light that is scattered at the lens interface may fall on the retina and exacerbate visual disturbances experienced by the patient. The perception of halos around bright-light sources has also been associated with diffractive optics, which may be an important factor for patient satisfaction [4]. Still, little is known about the amount of light scattered by the diffractive edges and how to quantify it precisely.

In numerous studies, various approaches have been applied to assess straylight from IOLs. Langeslag et al. used a goniometer setup [5] that van den Berg and IJspeert had first introduced to study straylight from normal and cataractous crystalline lenses of donated eyes [6]. Langeslag and colleagues found increased straylight at a broad angular range in diffractive compared to non-diffractive IOL designs [5]. Papadatou et al. assessed contemporary multifocal models using a clinical C-Quant straylight meter with an adaptation for IOL testing [7] and reported comparable straylight values to a monofocal lens at an effective 7° angle [8]. This finding was in line with clinical studies, which have also indicated non-inferiority in terms of ocular straylight of diffractive-refractive optics versus standard monofocal [9,10]. Another approach for IOL assessment was proposed by Arias et al. that utilizes an optical integration method and found straylight elevation in diffractive-multifocal IOLs when tested against a monofocal control [11]. None of those approaches, however, allow for selective zone analysis to determine the

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contribution of the diffractive steps to measured straylight, which may also be confounded by other kinds of scattering. Such precise quantification may also improve the estimate of the light loss in diffractive-refractive multifocal IOLs, which typically accounts solely for the redirection of light to higher diffractive orders [12].

This study proposes a method to quantify straylight from diffractive steps using a modified goniometer-based setup. Since the scattered light is effectively lost from the proper image, its quantification due to diffractive optics was a secondary objective. This new technique was tested using a contemporary refractive-diffractive IOL.

2. Materials and methods

2.1. Sample IOL

We used +20D Tecnis Symfony ZXR00 (Johnson & Johnson Surgical Vision, Inc., USA), a refractive-diffractive IOL made of hydrophobic material with a refractive index of 1.47 at 35°C. The IOL has an aspheric anterior profile to compensate for a corneal spherical aberration of 0.27 µm. Symfony's echelle diffractive pattern (placed at its posterior surface) consists of 9 zones that are used to produce two foci. In addition to the refractive-base power, it uses the 1st and the 2nd diffractive orders for far and intermediate vision [13]. Millán and Vega demonstrated that the 1st order's addition is 1.75D, and that of the 2nd order is 3.50D, compensating for lower base power. Hence, for the available sample, the base-lens power would be 18.25D, but in simultaneous action with diffractive optics, it has +20D in the 1st order and 21.75D in the 2nd. In addition to a high Abbe number of 55, the Symfony utilizes its diffractive approach ($m \neq 0$) to lower chromatic aberration effects at both foci since the correction can only take place when a diffractive element has refractive power [13,14]. The proximity of these designed foci creates an extended-depth-of-focus (EDoF) effect.

2.2. Straylight measurement technique

Figure 1 shows the arrangement of optics and instruments for measuring straylight.

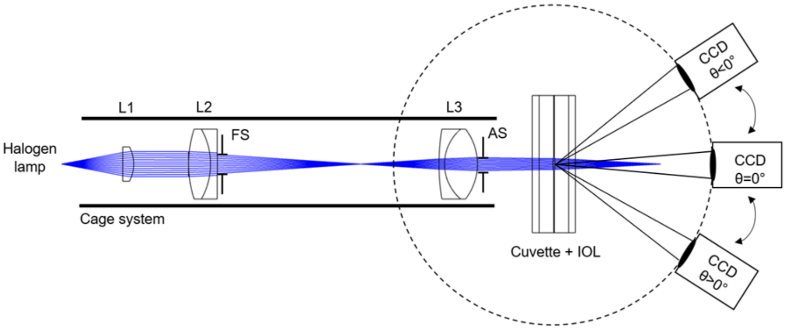

Fig. 1. Goniometer-based optical setup for light scattering assessment from diffractive-refractive IOLs. L = lens; FS = field stop; AS = aperture stop; CCD = charge-coupled device.

In brief, it consists of a light source, a condenser, a beam reducer, and a camera. The illumination system employs a 150 W high-output halogen lamp with variable intensity control (OSL2, Thorlabs GmbH, Germany). The light source features a fiber bundle that is connected to a collimation system with a plano-convex lens (L1). A beam reducer is composed of two achromatic lenses (L2 and L3) to minimize longitudinal chromatic aberration of the setup. A circular aperture, which also serves as a field stop (FS), is projected onto the IOL under test, exposing its central 4.84-mm diameter. An adjustable diaphragm placed after the last lens is the system's aperture stop (AS). A camera lens with a 5-mm aperture images the circular aperture at a 16-bit camera (pco.panda 4.2, PCO GmbH, Germany), which at a 51-mm distance yields a solid angle (Ω) of $7.5 \cdot 10^{-3}$ sr. We placed the camera on a motorized rotation stage and recorded the aperture image from -10 to 10° in 1° steps in air, which corresponds to -7.5° to 7.5° in water. The IOL was placed on a 3D-printed holder and submerged in saline that filled a cuvette. Finally, the sample was mounted on an XY translation stage for evaluation. Two Symfony samples of recent manufacture were measured, and the mean ± standard deviation (SD) was reported.

2.3. Image analysis

Recorded images of the circular aperture were processed using a customized MATLAB (MathWorks Inc., USA) program. Given that the direct beam confounded registered images at 6° and lower angles, we performed morphological structuring operations to retrieve light-scattering sources and remove the overlaying background. Figure 2 presents a photo before and after such operations at 3°. Images taken at higher angles than 6° were assessed without morphological processing.

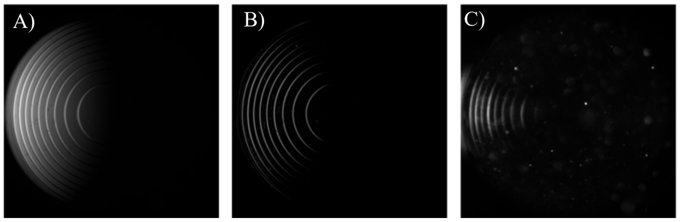

Fig. 2. Lens photograph at 3° (A) and a post-processing image (B) obtained after applying morphological operations to subtract the direct beam; C) shows an image (6.75°) where morphological processing was not necessary.

At each diffractive-step edge, we observed light scattering: in total, 9 arcs of light which correspond to Symfony's 9 steps in its echelle-grating design (Fig. 2). We used these observed arcs of light to define each zone (Fig. 3), allowing us to assess the light-scattering contribution of each edge to straylight and, thus, the loss of light. We set the zone border to fall halfway between each detected diffractive step. Besides the central and 9 annular zones, we also assessed a full aperture with a diameter identical to the outer diameter of the last (9th) zone. Note that since the zones have different surface areas, they do not contribute equally to the full aperture recording. We accounted for this by weighting their contribution by the area. However, to determine functional straylight, further weighting by the Stiles–Crawford effect of the first kind is needed.

Light scattering (i.e., straylight) was integrated from images at the recorded angles and weighted by the direct beam contribution and the solid angle. It corresponds to the outer part of the functional point spread function (PSF) [15]

$$\int PSF(\theta) d\omega = 1 \quad [sr^{-1}]$$

and is expressed by means of the straylight parameter (s)

$$s = \theta^2 \cdot PSF(\theta) \quad \left[\frac{deg^2}{sr}\right]$$

at an angular distance θ from the straylight source. In a clinic, however, most often, straylight is presented logarithmically as log(s).

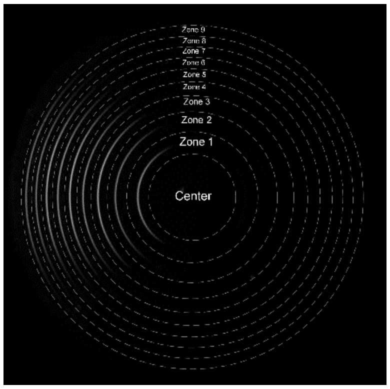

Fig. 3. Zone selection for image processing and data analysis.

The light-loss was derived from the scattered fraction, i.e., the integration of the recorded PSFs over a θ range of ±0.75° to ±7.5°. Since the scattered light does not contribute to forming an in-focus image, its quantification indicates what portion of the light is lost due to forward scattering.

3. Results

3.1. Straylight assessment

Figure 4 presents the straylight parameter of the Symfony across the angular range of -7.5° to 7.5°.

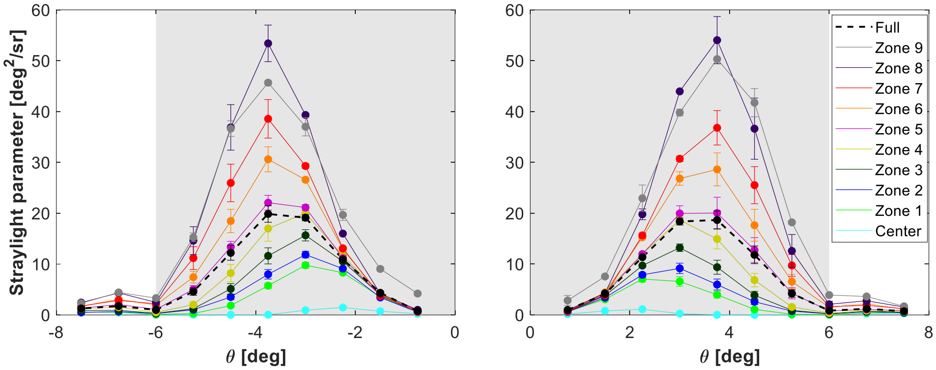

Fig. 4. Straylight parameter of a diffractive-refractive IOL measured in the refractive lens area (Center) and for each echelle zone (Zones 1 to 9). The dashed black line indicates light scattering of the whole lens (Full). The gray area indicates the angular range at which the photographs taken required morphological operations. Error bars = standard deviation.

The center of the IOL that is free of the diffractive structure shows straylight mostly below 1 deg^2/sr. However, the lens zones occupied by the echelle steps demonstrated a varying level of straylight elevation. An increasing straylight elevation was observed with increasing zone number with only the 9th step not following this pattern. Figure 4 confirms the symmetry in the light scattering intensity between positive and negative angles. The four first zones showed the maximum intensity occurring at 3°. For the remaining diffractive steps, this maximum shifted to 3.75°. The 8th echelle structure had the highest recorded value of 53.4 ± 3.6 deg^2/sr at -3° and 54.0 ± 4.6 deg^2/sr at 3°. Given the weighting factor of the zone area, the light scattering over the entire (Full) lens region was lower. The peak straylight parameter of the total lens area occurred at ±3.75° and was 19.9 ± 1.6 deg^2/sr (negative direction) and 18.7 ± 1.8 deg^2/sr (positive direction). At angles equal to and larger than 6°, all zones exhibited lower scattering effects with the full-aperture value around 1 deg^2/sr.

3.2. Light loss

Figure 5 presents the scattered fraction of light detected at each zone, which does not contribute to image formation, and, thus, can be considered lost.

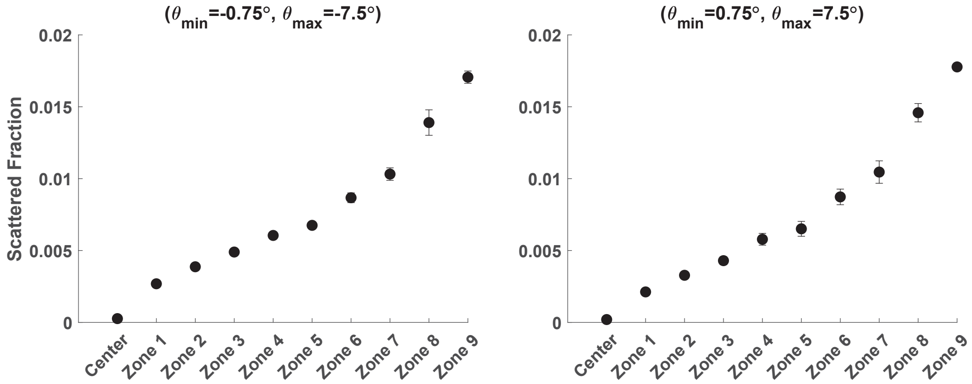

Fig. 5. Scattered fraction at each lens area. The fraction of scattered light was derived from the integration of the PSF recorded at the studied angular (θ) range.

The entire (Full) lens area yielded the total percentage of recorded scattered light of 6.2% ± 0.1% for both angular ranges. Like the straylight parameter distribution, the scattered fraction demonstrates a gradual increase of the recorded scattered light with increasing zone number, which was the highest for zone 9.

4. Discussion

We presented the goniometer-based method for precise quantification of light scattering originating from selected diffractive steps. We found in the assessed samples that the diffractive grating is a direct source of straylight with maximum intensity between 3° and 3.75°, which may pose a challenge in a clinical evaluation of this phenomenon.

Diffractive (multifocal) optics in IOLs have often been associated with visual disturbances [2,16]; however, it has not yet been elucidated how light scattering at diffractive steps contributes to glare perception. In our study, we confirmed that each ring is a source of straylight, which by definition, results in glare [17]. Although the functional effects of diffractive grating's light scattering must be weighted by the refractive lens area, which lowers its impact (Fig. 4), the straylight elevation was apparent. On the other hand, the straylight parameter of the non-diffractive part of the samples (Center) was close to or below 1 deg^2/sr. For comparison, a 20-year-old crystalline lens yields a higher value at an angular range of ±0.75° to ±7.5°, which is about 3 deg^2/sr, on average, as can be derived from a model proposed by the Commission Internationale d'Éclairage (CIE) [17]. This finding of minute material (bulk) scattering agrees with the results of earlier research. In a study by our group, the C-Quant device was used to measure the light scattering of contemporary hydrophobic IOLs prior to being subjected to accelerated-aging procedures [18]. The clinical straylight meter, which assesses straylight at an effective angle of 7°, was adapted for testing IOL samples [7]. The values found in that study ranged from 0.1 to 1.3 deg^2/sr [18]; thus, the 0.4 ± 0.1 deg^2/sr at 7° reported here confirms those C-Quant derived results.

Langeslag et al. measured straylight of monofocal and multifocal IOLs made of various materials [5]. They used two optical arrangements, for angles below 3° and up to 22°, which show parallels with the one we used in the current research. In their study, however, a slit-target was used, which limits the precise quantification of straylight from diffractive steps. Instead, the average over a refractive base and diffractive element is taken. In their evaluation of a ZCB00 model, they found approx. 2 deg^2/sr up to 3°, and approx. 0.2 deg^2/sr at 7° [5]. Since the Symfony is made of the same material, a comparable value can be expected in the lens center (i.e., without echelles), which is in line with our findings. Langeslag and colleagues also reported an increased straylight of a diffractive-refractive bifocal IOL (ZMB00) from the same manufacturer, which was noted at lower angles. At 2°, they found values close to 3 deg^2/sr, which contrasts with 11.1 ± 0.3 deg^2/sr at 2.25° of the current study measured with the full aperture. The Symfony and the ZMB00 are manufactured from Tecnis material [19]; hence, the observed straylight increase may result from differences in the diffractive design. The EDoF model uses the 1st and 2nd diffractive orders to divert the light to far and intermediate foci [13], in contrast to a 0th/1st design of a classic bifocal lens [20]. One advantage of the 1st/2nd order approach is the possibility of (partially) correcting longitudinal chromatic aberration of the eye [13,14,21]. However, higher-diffractive orders require a higher step height of the echelle grating, which may lead to increased light scattering at the diffractive zones. However, more research is needed to determine the association between straylight and step height in diffractive-refractive IOLs

Arias et al. proposed a different explanation for Symfony's straylight elevation [11]: nonhomogeneous micro-rings observed in specular microscopy by Gatinel and Loicq [19]. Arias and colleagues applied an optical-integration technique, which quantifies straylight <5.1°, and a car's headlights recording to compare photic phenomena of a monofocal, EDoF (i.e., Symfony), and a trifocal lens. The average over 1°-5.1° range of the three models was 1.2 deg^2/sr (monofocal), 12.1 deg^2/sr (trifocal) and 33.4 deg^2/sr (EDoF) [11]. The headlights visualization confirmed an increased halo size produced by the EDoF lens. Arias et al. reported an intensity peak of the Symfony to occur at 1.81°. We noted the maximum at 3° for the four first zones and 3.75° for the remaining echelle structures, indicating a close correspondence. In the current study, the largest recorded value over the full aperture was 19.3 ± 0.8 deg^2/sr. Despite these differences in the absolute straylight parameters, which may result from the different methodologies used, both studies indicate straylight elevation at lower angles for the Symfony.

The angular location of the straylight maxima found in the studied EDoF model makes it challenging to detect using standard clinical means. For instance, the C-Quant device provides a straylight value that is averaged over 5° to 10° [7,8,22]; at this range, we did not observe much straylight elevation. It was confirmed in a laboratory evaluation of the Symfony with the C-Quant adaptation, which showed a mere value of 0.50 ± 0.13 deg^2/sr [8]. Our findings agree with the clinical results of Monaco et al., who, among other visual-function parameters, compared straylight of patients implanted with a monofocal, a trifocal, or the Symfony lens [10]. They did not find a statistically significant difference between the studied models, with the Symfony patients scoring 0.86 ± 0.21 log(s). This is equivalent to 7.2 deg^2/sr, which is very close to the level of a young eye [17], so the contribution of the implanted IOL is minimal. This can be understood in view of the current results as above 5° the EDoF introduces ~1 deg^2/sr (full aperture). At 7° (C-Quant's effective angle), we found 0.4 ± 0.1 deg^2/sr, which is below the measurement error reported by Monaco et al. Given virtually no difference between the lens (monofocal) center and the full aperture (refractive-diffractive) measurements at 7°, the comparable straylight levels of monofocal and EDoF patients can be explained. Therefore, a straylight assessment should be extended to lower angles (e.g., using a modified C-Quant meter with a 2.5° scatter angle [22,23]) to clinically determine the effect of the observed straylight elevation at the echelle grating.

The clinical evaluation of photic phenomena in Symfony patients has been performed in numerous studies. Ukai et al. studied the characteristics of the perceived glare, halo, and starburst in a trifocal, an EDoF (i.e., Symfony) and a monofocal lens [24]. A screen-based simulator was used with a light-emitting diode in the center to quantify visual symptoms. Ukai et al. reported a significantly increased halo size associated with the presence of the EDoF lens compared to the trifocal one. The patients perceived halo rings of varying intensity, which may correspond to the phenomenon observed in the current study. Therefore, light scattering at diffractive steps, as studied here, may indeed contribute to patient-reported photic phenomena and influence patient satisfaction. Miháltz et al. applied a questionnaire and found a large proportion (47%) of Symfony patients unsatisfied with their postoperative vision [4]. Among residual astigmatism and compromised near vision, pupil size and the perception of halos were identified as factors affecting patients' assessment of the postoperative outcome. Still, none of Miháltz et al. cases required explantation, suggesting that although noticeable and bothersome, the reported halos are not debilitating enough to outweigh the risk of a secondary procedure. Monaco et al. also assessed the incidence of photic phenomena through a questionnaire [10]. They found that the proportion of patients reporting halos ("Quite Often") was higher in the Symfony group compared to the trifocal one (25% vs. 15%). The current study's results may help understand the origins of these complaints and provide a tool for their objective quantification.

Straylight is mainly associated with glare phenomena [17,22], but its secondary consequence is that the light is lost, i.e., it is spread over the retina and does not contribute to the image projection. The loss of light related to diffractive optics has been a well-known limitation [12]. For a classic $0^{th}/1^{st}$ order kinoform design, it was 18-19% [12,20], which improved to 7.6-10% in a more recent sinusoidal profile [25]. The Symfony's efficiency was estimated in a grating-groove metrology study to be between 16-18% at 550 nm [13]. However, it is important to note that the efficiency changes substantially if other than the design wavelength is used [13,21,26]. The reported values refer to calculated diffraction efficiency at selected diffractive orders [12,13,20,25]. Although light refraction to other than intended orders (i.e., foci) constitutes the largest portion of the estimated loss, other factors also add to this, such as light scattering at the echelle structure. The measurements conducted in the current study revealed an estimated value of $6.2\% \pm 0.1\%$ that does not fall into the design foci nor higher-diffractive orders due to the angular extent at which it was detected. Other factors are light transmittance and surface reflectance [27,28]. According to the manufacturer, Tecnis material's light transmission is close to 100% and appears to be limited only by light reflectance. Fresnel's reflection coefficient can be calculated based on the refractive index of the IOL (1.47) and the aqueous humor (1.336) [27,28], which gives 0.5% for anterior and posterior surfaces. Therefore, the total value of the light loss should be corrected by 6.7% to account for forward light scattering and surface reflectance, which appears to be more representative of an in vivo situation.

The limitation of the current setup is that it requires morphological image processing to remove the direct beam confounding the background, which may underestimate the effect of diffractive steps and add to the uncertainty of the measured values. Various models demonstrate varying background intensity and distribution; hence, the approach requires customization depending on a lens model. Also, the analysis of the diffractive profile at the periphery may be affected by vignetting, which may explain lower straylight values of the 9th than the 8th echelle. The decreasing spacing between diffractive steps of IOLs with higher add powers may also pose a challenge in evaluating the contribution of peripheral zones. However, measurements within the central 4.5-mm area showed good reproducibility and angular symmetry of the recorded values confirming the suitability of the proposed method for the assessment of light scattering from diffractive IOLs.

5. Conclusions

The goniometer-based method to quantify light scattering from diffractive steps has been proposed and tested using the EDoF lenses utilizing the $1^{st}/2^{nd}$ diffractive orders. The refractive-lens base exhibited only a slight scattering effect, which conforms with laboratory and clinical studies. However, the echelle pattern introduced straylight elevation with the peak intensity between 3° and 3.75°. Still, such effects are minimal at 7°, which may explain the C-Quant's inability to differentiate between the Symfony and a monofocal lens. A clinical study with a modified straylight meter, such as one described elsewhere [22,23], could verify this laboratory finding. Since the scattered light is missed in the retinal image, its proportion reflects the light loss. This should be included along with the diffractive efficiency and biomaterials' light transmittance to comprehensively estimate this parameter in refractive-diffractive IOLs.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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