Optical Measurement of Straylight in Eyes With Cataract

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ABSTRACT

PURPOSE: To measure straylight in a cohort of patients with cataract using a novel optical instrument and to correlate optical straylight values with clinical grade of cataracts and psychophysical straylight values.

METHODS: Measurements were performed on 53 eyes of 44 patients with cataract admitted to the ophthalmology service of the university hospital in Murcia, Spain, and 9 young volunteers with no known ophthalmic pathology. Lens opacities were classified according to the Lens Opacities Classification System III (LOCS III) under slit-lamp examination. Intraocular straylight was additionally assessed psychophysically using the C-Quant straylight meter (Oculus Optikgeräte GmbH, Wetzlar, Germany).

RESULTS: Optical measurements of the logarithm of the straylight parameter ranged from 1.01 to 2.01 (mean: 1.43 ± 0.244) in patients with cataract and 0.80 to 1.08 (mean: 0.92 ± 0.104) in healthy young volunteers. Straylight differed by a statistically significant amount among different LOCS III groups ($P < .05$). Moreover, the optically measured straylight parameter was positively correlated to the psychophysically estimated value ($r = 0.803$, $P < .05$).

CONCLUSIONS: A new compact optical instrument suitable for clinical measurements of straylight in the human eye has been developed. Optically measured straylight values were highly correlated to those that were obtained psychophysically. Optical measurement of straylight can be used for the objective classification of cataract opacities based on their optical impact.

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Light scattering in the crystalline lens is a primary cause of image deterioration in cataract. Straylight in the human eye, as a result of light scattering, degrades image quality and deteriorates visual performance, especially when glare sources are present in the visual field.[1,2]

This work pertains to the use of a novel instrument[3] for the measurement of straylight in a cohort of patients with cataract. The instrument measures straylight in the forward direction and therefore provides information on the visually relevant amount of straylight, which may be different[4,5] from backscattered light that is typically observed in a clinical examination. The instrument is different from existing double-pass instruments because it uses visible (green) light and measures straylight at wider angles.[3] The rationale of this study was to validate the new instrument in a clinical setting and to evaluate its effectiveness in the characterization of cataracts in a clinically useful manner.

The need for standardization in diagnosis and streamlined decision-making in the treatment of cataract has led to various approaches for the classification of cataracts or the quantification of their optical effects.

In clinical practice, cataracts are often classified by the Lens Opacities Classification System (LOCS III).[6] In the LOCS III, slit-lamp images of the crystalline lens are matched to photographic records of categorized cataracts in respect to the den-

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Drs. Ginis and Artal have a patent on the optical instrument for the measurement of straylight used in this study. The remaining authors have no financial or proprietary interest in the materials presented herein.

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sity, localization, and coloration of the opacities. For the current study, we selected nuclear opalescence as a single parameter to express the severity of cataracts.

The method of compensation comparison[7] for the psychophysical assessment of straylight has been used for the measurement of straylight in eyes with cataract.[8] Straylight values that may be an indication for cataract surgery have been suggested.[9] This approach cannot be performed by every patient and requires time and dedication for the examination.

Optical measurements of forward straylight using the new optical instrument were performed in a cohort of patients with cataract. The optical measurements of straylight were compared to the psychophysical measurements of straylight and also to the subjective classification under the LOCS III system.

PATIENTS AND METHODS

Optical Instrument

The peripheral skirt of the point-spread function in the human eye (angles ranging from 3° to approximately 30°) can be approximated by an inverse square law often referred to as the Stiles–Holladay law[1,2] (point-spread function [θ] = S / θ^2). Although different mechanisms can contribute to straylight in the eye, this empirical approximation is remarkably accurate and indicates that the amount of straylight can be quantified using a single parameter S (straylight parameter). The instrument performs straylight measurements in a range of angles between 3° and 8° and quantifies it as the S parameter described above.

The new instrument for the measurement of straylight, named Sigma, is based on previous experience with imaging double-pass systems for the measurement of the point-spread function of the eye[10] combined with the projection of extended discs (rather than a point source) according to the method of optical integration.[11] With this approach, the sensitivity and the dynamic range of the measurement are greatly increased, making it possible to evaluate straylight for visual angles up to approximately 8°.[11] Experiments with various wavelengths indicated that optical measurements should preferably be performed at wavelengths near the peak of the spectral sensitivity of the eye.[12] In this part of the spectrum, artifacts related to the diffusion at the ocular fundus are avoided and straylight is measured at the wavelength that is most significant for vision. The instrument, described previously in detail,[3] uses a light source based on an array of green (528 ± 10 nm) high brightness light-emitting diodes (LEDs) spatially homogenized by diffusers. The source is divided in two concentric zones, a disc corresponding to a visual angle of 3° (radius) and an annulus (3° to 8°, corresponding to the straylight measurement range). The LEDs are square-wave modulated at 483 and 769 Hz for the disc and the annulus, respectively. This source is projected onto the fundus and the reflected light from the central part of the fundus (approximately 1°) is coupled to a silicon photomultiplier device (Excelitas, Waltham, MA). Projection is made through the upper half of the pupil and imaging through the lower half to avoid backscattering and spurious reflections. The Fourier transform of the recorded signal reveals the contribution of the annulus and the disc in the reflected signal. From this information the straylight parameter can be estimated.[3] **Figure 1** shows a schematic representation of the instrument's optical layout and its principle of operation.

Patients and Clinical Examination

In this study, 44 patients with cataract (mean age: 62.9 ± 5.08 years; range: 55 to 72 years) who were randomly recruited at the ophthalmology service of the Hospital Virgen de la Arrixaca of Murcia and 9 young healthy volunteers (mean age: 34.6 ± 6.75 years; range: 28 to 45 years) were enrolled. Although measurements were performed in both eyes, only one eye of the patients and healthy volunteers was used for the statistical analysis. After the standard clinical examination, patients with no pathology other than mild to severe nuclear cataract were informed about the objectives and methods of the current study. Those who consented underwent three consecutive measurements with the optical instrument (Sigma). The average value of these three measurements was used for analysis. The measurements were performed in an examination room with dim ambient light to allow natural pupil dilation.

Additionally, a subjective grade for each eye was obtained after classification according to the LOCS III system based on slit-lamp photographs acquired during clinical examination. The value reported is the nuclear opalescence. A single investigator who was blind to the straylight data performed all classifications.

Finally, straylight for each eye was measured psychophysically by using the compensation comparison method (C-Quant straylight meter; Oculus Optikgeräte GmbH, Wetzlar, Germany). After the psychophysical measurements, the patients received 1% tropicamide and 10% phenylephrine eye drops for mydriasis and the optical measurements were repeated.

The optical measurements were not feasible for 2 cases with small pupil diameters (< 4 mm) prior to dilation. Furthermore, 5 patients with cataract could not complete the psychophysical measurement with the C-Quant straylight meter.

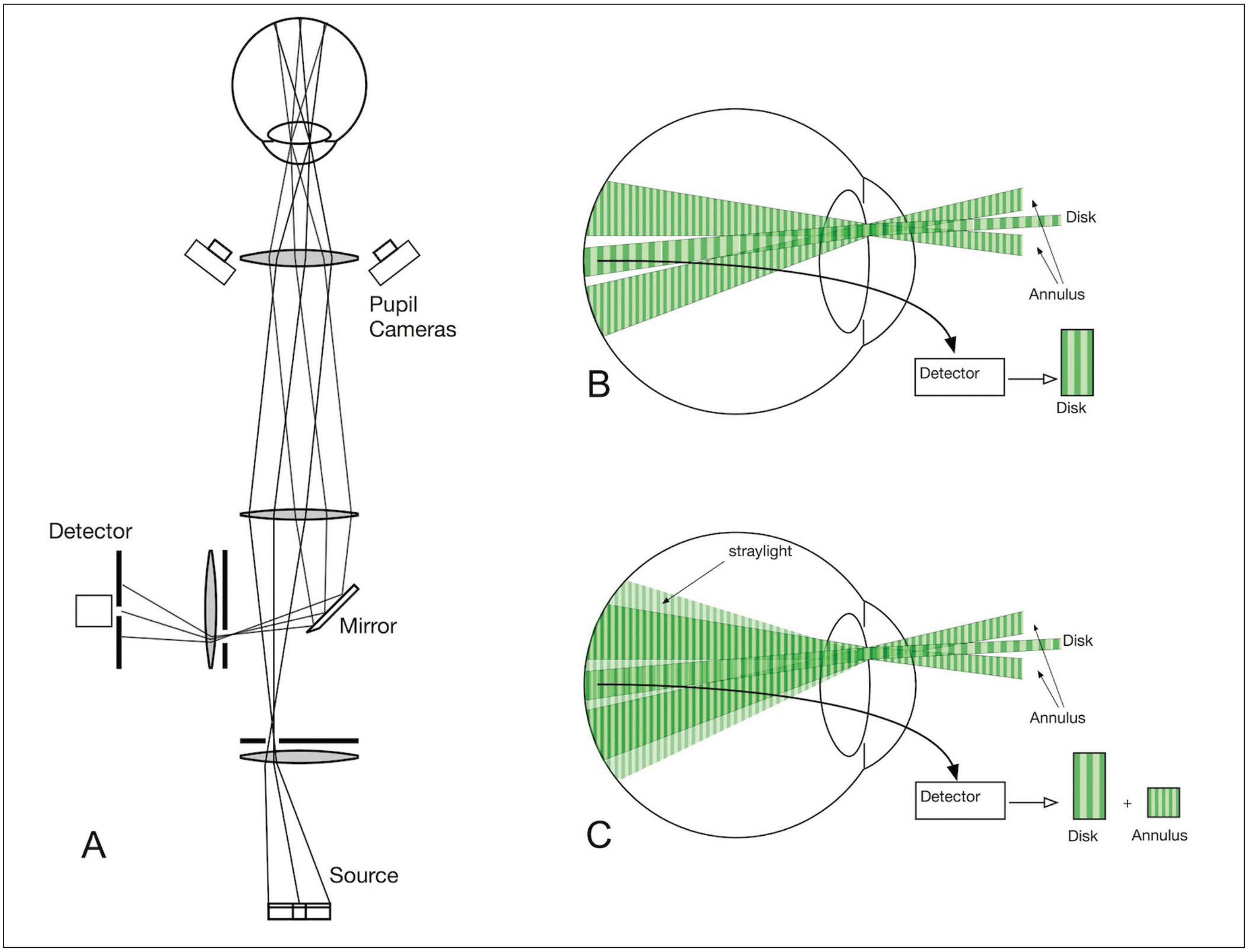

Figure 1. (A) Optical layout of the illumination and recording arms. (B) Hypothetical eye with no scattering. The detector only receives a signal from the central disc. (C) Light scattering directs some light from the annulus into the central part of the field. The detector receives both the disc and annulus signal. The ratio of these signals is used to derive the straylight parameter S.

Statistical Analysis

SPSS for Windows software (version 22.0; IBM Corp., Armonk, NY) was used for the statistical analysis and interpretation of the data. Kolmogorov–Smirnov and Shapiro–Wilk tests for testing the normal distribution and Levene's test for testing the equality of variances were used. Furthermore, two-tailed paired samples *t* test analysis was applied for the comparison of the results across the psychophysical and optical methods (before and after dilation). The Bland–Altman method and two-tailed paired samples *t* test were used to analyze the agreement between the two different methods of quantification of intraocular scattering. Additionally, analysis of variance with Bonferroni correction was used to analyze differences in optical straylight measurements between LOCS III groups.

RESULTS

The resulting *P* values of the Kolmogorov–Smirnov and Shapiro–Wilk tests revealed homogeneous distribution of psychophysical and optical straylight measurements with/without dilation (all $P > .05$). The Levene's test verified the equality of the variances (homogeneous of variance) ($P > .05$).

The two-tailed paired sample *t* test revealed a statistically significant difference (mean: 0.061 ± 0.14; spherical equivalent [SE] = 0.020; $t = 3.033$; $df = 50$; $P = .004$) between the optical measurements of straylight before (mean: 1.34 ± 0.29; n = 51; SE = 0.042) and after dilation (mean: 1.28 ± 0.27; n = 51; SE = 0.039). The statistical outcome also showed high correlation between the two measurements ($r = 0.879$, $P < .001$). Although the statistical analysis revealed that the 0.06 log(S) difference was significant, this difference is not

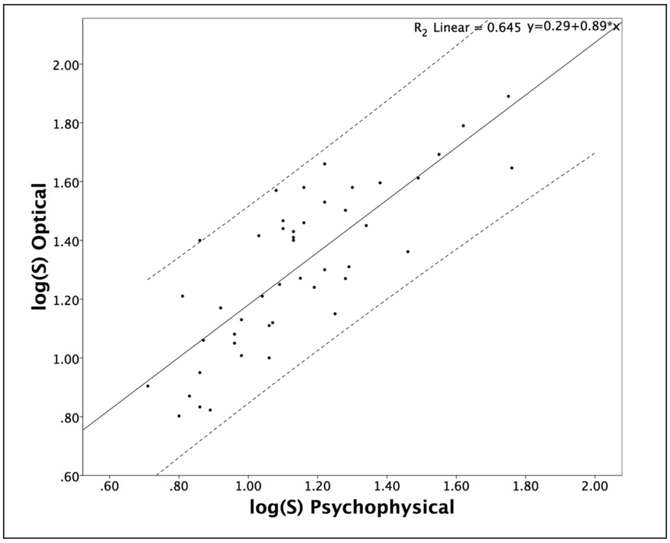

Figure 2. Scatter plot showing the correlation between psychophysical and optical measurements of straylight (solid line is diagonal for reference).

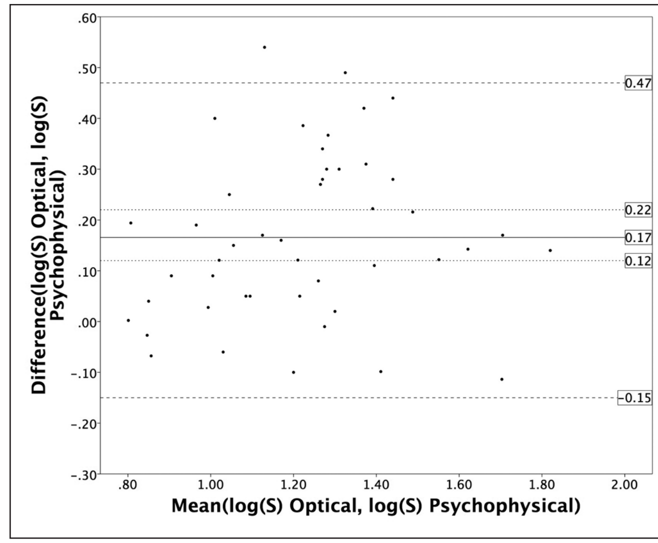

Figure 3. Bland–Altman plot to evaluate the agreement between the optical and psychophysical measurements.

of clinical importance. Thus, the following results pertain to the optical measurements without dilation.

The mean value of log(S) was 1.30 ± 0.27 (n = 46; SE = 0.040) for the optical and 1.14 ± 0.24 (n = 46; SE = 0.036) for the psychophysical measurement. The mean difference of log(S) was statistically significant (mean: 0.17 ± 0.16; SE = 0.024; t = 6.851; df = 45; $P < .001$). The correlation of the psychophysical and the optical measurement was statistically significant and the Pearson correlation coefficient was 0.803 ($P < .001$). The correlation of the optical and the psychophysical measurements is shown in **Figure 2**.

Bland–Altman analysis (**Figure 3**) was also used for further understanding of the agreement between the two different methods of quantification of intraocular scattering. The calculated variables (differences and averages) for Bland–Altman analysis were normally distributed (Kolmogorov–Smirnov and Shapiro–Wilk, $P > .05$) and equality of the variances were verified (Levene's, $P > .05$). The differences of means for the optical and the psychophysical measurements were significant. The mean difference was 0.17 ± 0.16 (SE = 0.02). The line of equality was not within the confidence intervals (down: 0.12, up: 0.22). Thus, the bias was significant. Furthermore, linear regression analysis revealed there was no proportional bias ($P > .05$) (**Figure 3**).

An anaylsis of variance test with Bonferroni correction was used to reveal the difference of the optical measurements of straylight in the following groups (healthy volunteers, grade 1 and 1.5, grade 2 and 2.5, grade 3 and 3+). The results (**Figure 4**) revealed statistically significant differences between groups ($P < .004$).

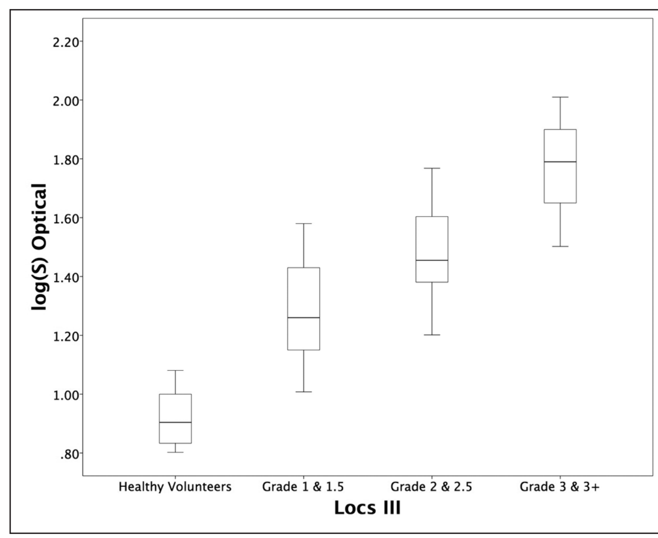

Figure 4. Straylight values for different Lens Opacities Classification System III (LOCS III) groups. Data of young healthy volunteers are plotted for reference.

DISCUSSION

A new optical instrument for the measurement of straylight in the human eye (Sigma) had been previously validated in laboratory conditions using standard diffusing filters[3] and a limited number of young healthy volunteers. The current study pertains to the application of this technology in a clinical setting to evaluate its efficiency in detecting different amounts of straylight in a larger population and compare its measurements with subjective classification of cataract (LOCS III) and with psychophysical straylight measurements (C-Quant straylight meter).

Previous experience with double-pass optical methods has shown that it is possible to use a double-pass instrument to characterize the severity of cataracts.[13] In a recent study using a commercial version of the double-pass method (HD Analyzer; Visiometrics SL, Terrassa, Spain), Galliot et al.[14] reported that the method is sensitive and efficient for the early detection of cataract in patients. A variant of the double-pass method using a Shack–Hartmann sensor has been recently introduced for the objective straylight assessment in the human eye.[15] The instrument quantifies straylight in a clinically relevant parameter (S, the straylight parameter) using visible light, is sensitive,[3,10] and is by design minimally affected by artifacts associated with the diffuse fundus reflectance[12] and residual refractive errors and aberrations.[3]

The optical instrument quantifies straylight in the forward direction that is relevant to the optical effects of cataracts.[4,5] The measurement is performed in the central zone of the pupil having a diameter of 4 mm. In the case of nuclear cataracts (as in the current study), it is possible that the optical measurement overestimates the severity of straylight when compared to other measurements involving wider pupils, such as the psychophysical measurement (C-Quant straylight meter) that was performed in a generally wider natural pupil. Moreover, it must be kept in mind that although the two instruments report the same quantity (the straylight parameter), they arrive at its value using different methods and assumptions. The Sigma instrument analyzes scattering in the optics of the eye to estimate the straylight parameter, whereas the C-Quant straylight meter uses a psychophysical task to estimate a visual value.

The optical technique is performed quickly and without requiring the patient's active participation. The optical measurement of straylight with the sigma instrument is feasible in all eyes that have a pupil diameter larger than 4 mm. This requirement is defined by the instrument's design and is related to the fact that fixed parts of the pupil are used for illumination and sensing. Measurements in eyes with smaller pupil diameters are not recommended because backscattering from the iris and blocking of the returning light from the fundus may result in measurement error.

We have used a compact optical straylight meter for the first time in a clinical setting. It allows quick measurements of a straylight parameter in both healthy eyes and eyes with cataract under standard clinical conditions. This new instrument may be a step toward the comprehensive evaluation of the optics of the human eye in the diagnosis and treatment of cataract.

AUTHOR CONTRIBUTIONS

Study concept and design (OS, AP, HG, IP, PA); data collection (LH, EAV, BC); analysis and interpretation of data (OS, AP, LH, IP, JMM, PA); writing the manuscript (OS, AP, HG, BC, PA); critical revision of the manuscript (OS, AP, HG, LH, EAV, JMM, PA); statistical expertise (OS); administrative, technical, or material support (OS, IP); supervision (JMM, IP, PA)

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