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ORIGINAL ARTICLE

The significance of changes in pupil size during straylight measurement and with varying environmental illuminance

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Ocular straylight;
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Room illuminance

Abstract
Purpose: In this work, we investigated the pupillary conditions during straylight measurement, and the potential effect this might have on the measured straylight.
Methods: Five young (26–29-years-old) and 15 older (50–68-years-old) individuals participated in this study. First, the pupil diameter of both eyes was measured at three room illuminances. Next, straylight was assessed at two room illuminances. Simultaneously, the change in pupil size of the fellow eye was registered by a camera.
Results: Pupil size decreased with room illuminance and with age (both $p < 0.05$). The dependency of pupil size on age decreased as room illuminance increased (0.018 mm/year at 4 lux, 0.014 mm/year at 40 lux, and 0.008 mm/year at 400 lux illuminances). However, during straylight measurement, pupil sizes hardly differed between 4 and 40 lux illuminances. Respective pupil sizes corresponded with 399 and 451 lux adaptation on average. No statistically significant difference was found between the straylight under the two illuminances with average $R^2 = 0.85$, $p < 0.05$.
Conclusion: We conclude that the illuminance of the examination room during straylight assessment does not affect the outcome in normal eyes. In fact, under mesopic and scotopic conditions, the luminance of the test field is so much higher than that of the room so that it determines the pupil size. Regardless of the lighting level, straylight measured in a laboratory, is valid for photopic pupils at an adaptation level corresponding with about 400 lux room illuminance.

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PALABRAS CLAVE
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Dispersión lumínica ocular;
C-Quant straylight-meter;
Iluminancia ambiental

Importancia de los cambios del tamaño de la pupila durante la medición de la dispersión lumínica, con variación de iluminancia ambiental

Resumen

Objetivo: En este trabajo investigamos las condiciones de la pupila durante la medición de la dispersión lumínica, así como el efecto potencial que ello podría tener sobre la dispersión lumínica medida.

Métodos: En el estudio participaron cinco individuos jóvenes (de 26 a 29 años) y 15 mayores (de 50 a 68 años). En primer lugar, se midió el diámetro de la pupila de ambos ojos con tres iluminancias ambientales. A continuación, se evaluó la dispersión lumínica con dos iluminancias ambientales. De manera simultánea, se registró mediante una cámara el cambio del tamaño de la pupila del otro ojo.

Resultados: El tamaño de la pupila se redujo con la iluminancia ambiental y la edad ($p < 0,05$ para ambos). La dependencia del tamaño de la pupila con la edad se redujo a medida que aumentaba la iluminancia ambiental (0,018 mm/año a iluminancias de 4 lux, 0,014 mm/año a 40 lux, y 0,008 mm/año a 400 lux). Sin embargo, durante la medición de la dispersión lumínica, los tamaños de la pupila difirieron escasamente entre iluminancias de 4 y 40 lux. Los tamaños de la pupila respectivos se correspondieron con una adaptación de 399 y 451 lux, de media. No se encontraron diferencias estadísticamente significativas entre la dispersión lumínica bajo las dos iluminancias y la media de $R^2 = 0,85$, $p < 0,05$.

Conclusión: Concluimos que la iluminancia de la sala de examen durante la valoración de la dispersión lumínica no afecta al resultado en ojos normales. De hecho, en condiciones mesópicas y fotópicas, la iluminancia del campo de prueba es muy superior a la de la sala, lo cual determina el tamaño de la pupila. Independientemente del nivel de iluminación, la dispersión lumínica medida en un laboratorio es válida para pupilas fotópicas a un nivel de adaptación correspondiente a una iluminancia ambiental de alrededor de 400 lux.

Introduction

The amount of vision loss caused by disturbances in the eye's optical media can be assessed by visual acuity testing. However, these disturbances can also cause forward light scattering.[1–6] This scatter generates a veil of undesired light on the retinal image, leading to decreased image contrast and color, increased glare and hazy vision. Such increased glare becomes alarming often when the individual stops driving at night. The loss of contrast, on the other hand, may lead to difficulties such as against-the-light face recognition. The amount of straylight is expressed by a single-valued number, called straylight parameter. This parameter is the ratio between the undesired light scattered by disturbances in the optical media which generates the veil on the retina, and the desired non-scattered light, which forms the retinal image.

An issue that has been previously studied,[7] is the effect of pupil size on straylight. It might be thought that straylight is more bothersome at night, because the larger pupil size allows more light to enter the eye causing more glare. Therefore, it might be thought that the amount of straylight changes under low environmental light intensity. However, one should consider the fact that as the amount of scattered light increases by the enlarged pupil, the amount of constructive light entering the eye also increases. In other words, the ratio between the destructive and constructive light is approximately constant. The study by Franssen et al. concluded that the amount of straylight measured in a small group of dominantly young subjects with normal eyes (four subjects younger than 37 years and one 59 years old), only weakly depends on pupil diameter. Therefore, straylight values obtained in healthy young eyes under photopic conditions are valid for mesopic and scotopic conditions as well.

The crystalline lens changes with age. The lens grows over time and its color changes from clear to milky to yellow and then brown in eyes over 65 years of age. An old lens, even the clearest one, is a substantial source of straylight.[8] Early studies[9–11] on ocular straylight in normal eyes reported that it increased with age. Later, several studies[12–14] have confirmed that straylight increases with age; dominantly due to changes in the lens, even in normal eyes. A question then arises as to whether changes in the crystalline lens in older eyes that cause an increase in straylight, changes the straylight independency of the pupil size. As shown in several studies,[15,16] pupil size decreases with age and with environmental illumination. It is thought that the effect of partial eye wall translucency may be more important in small pupil sizes.[7] This trait of eye wall makes it another source of straylight.

In the present study, we wanted to find out what the pupillary conditions are during straylight measurement, and what potential effect this might have on the measured straylight value. In other words, we investigated whether pupil size and straylight measured under dim room light conditions is the same as pupil size and straylight measured under dark room light conditions.

Methods

This study encompasses two parts: (1) The measurement of pupil diameter under various room illuminances; (2) The measurement of ocular straylight under various room illuminances. A group of 21 subjects, 6 of them between 26 and 29, and 15 of them between 50 and 68 years of age, all with normal pupillary responses were recruited from the staff of *Rotterdam Ophthalmic Institute*. Three of the younger subjects were non-Caucasian; the remaining 18 subjects were Caucasian. First part of the measurements were performed on all 21 subjects, however, the second part of the measurements were performed on 20 of them; one subject from the younger group dropped out. Exclusion criteria were pupillary anomalies (such as anisocoria, Argyll Robertson pupil, fixed pupil, and Hutchinson's pupil), pre-existing factors that can cause pupillary constriction, e.g. medications including narcotics and topical beta-blockers, a high refractive error (more than ± 3 diopters) or astigmatism, cataract and any eye infection or injury at the time of measurement. Informed consent was obtained after an explanation of the experimental protocol. This study was conducted in accordance with the principles of the Declaration of Helsinki (October, 2013), the guideline for Good Clinical Practice (CPMP/ICH/135/95) and the Medical Research Involving Human Subjects Act (WMO, 2006).

Images of the pupil diameter were taken using a Trust SpotLight webcam (with a 640×480 hardware resolution for obtaining a sharp image and powerful integrated infra-red LED lights with dim function for enhanced image quality in low-light environment) connected to a computer to register the images. All the measurements were performed on the subjects' non-dilated eyes without glasses or contact lenses. The distance between the measured eye and the webcam was 5 cm for all subjects. To measure the pupil diameter, we used a calibrated ruler and the diameter of the pupil in the image captured by the webcam displayed on the computer screen. The measurement of the latter was facilitated using autoCAD. The sensitivity of the measurements was 0.01 mm.

Part 1: Pupil change with changes in illuminance level

Pupil diameter was measured at three levels of room illuminance, 4, 40, and 400 lux, measured at the table surface. To eliminate the effect of hippus, a fifteen-second adaption time to each level of illumination was given. Measurements were carried out from the lowest to the highest level of illumination. Fig. 1 shows images of a pupil under the three different illuminances. Results of pupil size measurements are plotted against age for three levels of illuminance in Fig. 2.

Part 2: Straylight change with changes in illuminance level

Ocular straylight was assessed using a commercially available straylight-meter (C-Quant, OCULUS, Germany).[17] The C-Quant straylight-meter works based on the compensation comparison method, which compares the amplitude of a counter-phase flickering light required to compensate the induced flickering light produced by the straylight source. The device was connected to a computer set. To record the changes in pupil size, the Trust webcam was mounted against the tubus of the straylight meter and connected to a computer set. All the straylight measurements were performed on subjects' one eye while the other eye was under pupil size measurement. Both eyes had natural dilation, with no glasses or contact lenses. However, proper refractive trial glasses were added to the straylight-meter when needed according the practical guide of the manual. Each measurement provides an expected standard deviation (ESD) and a quality factor (Q). Our instrument considered the measurement optimal when $ESD < 0.08$ and $Q > 1$. The measurement was repeated if the device considered it sub-optimal. Before repeating a measurement, the range setting was adjusted according the practical guide of the manual. It must be noted that these criteria are rather strict.[18]

We used the data from the first part of the study to estimate the adaptation level during straylight assessment. The pupil sizes of all subjects were regressed against the respective room illuminances. The pupil sizes during straylight measurement were used to estimate from the resultant linear relationship the adaptation level during C-Quant measurement.

Statistical analysis

All the calculations in this work are performed by using Microsoft Excel 2010 (Microsoft corp.). To investigate the strength of association of change in pupil size with the level of environmental illumination, we performed a Student's t-test. Having three levels of illumination, we have taken into account the Bonferroni correction. Average pupil size is plotted against three levels of illumination. The effect of age on pupil size is shown in Fig. 2. We can also see that this dependency decreases with increasing environmental illumination. Simple linear regression was used to describe the correlations. The correlation coefficient is calculated using the nonparametric method, the Spearman's r.

In the second part of the study, to investigate the strength of association of change in illumination with straylight value, we performed a paired t-test. The pupil size changes during the straylight measurement, as the intensity of the straylight source varies with each step. In the first half of the measurement (initial phase), a coarse assessment of the straylight value is achieved. In the second half of the measurement (final phase) the straylight value is assessed with precision using 13 presentations. For the effective pupil value, we chose to consider only the last 13 steps in the analysis. The fluctuation in pupil diameter in the last 13 steps is illustrated in Fig. 4. The average pupil size during the straylight measurement under 4 lux-illumination condition is plotted against that under 40 lux-illumination condition in Fig. 3.

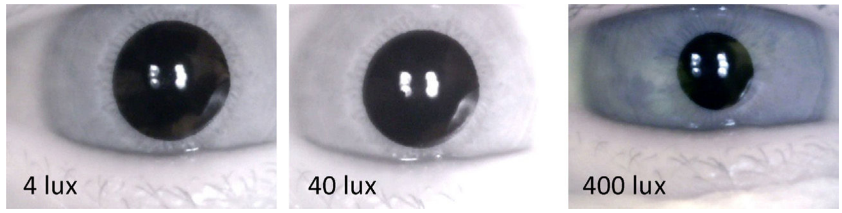

Figure 1 Changes of a pupil under three environmental illumination levels for a subject of 56 years of age.

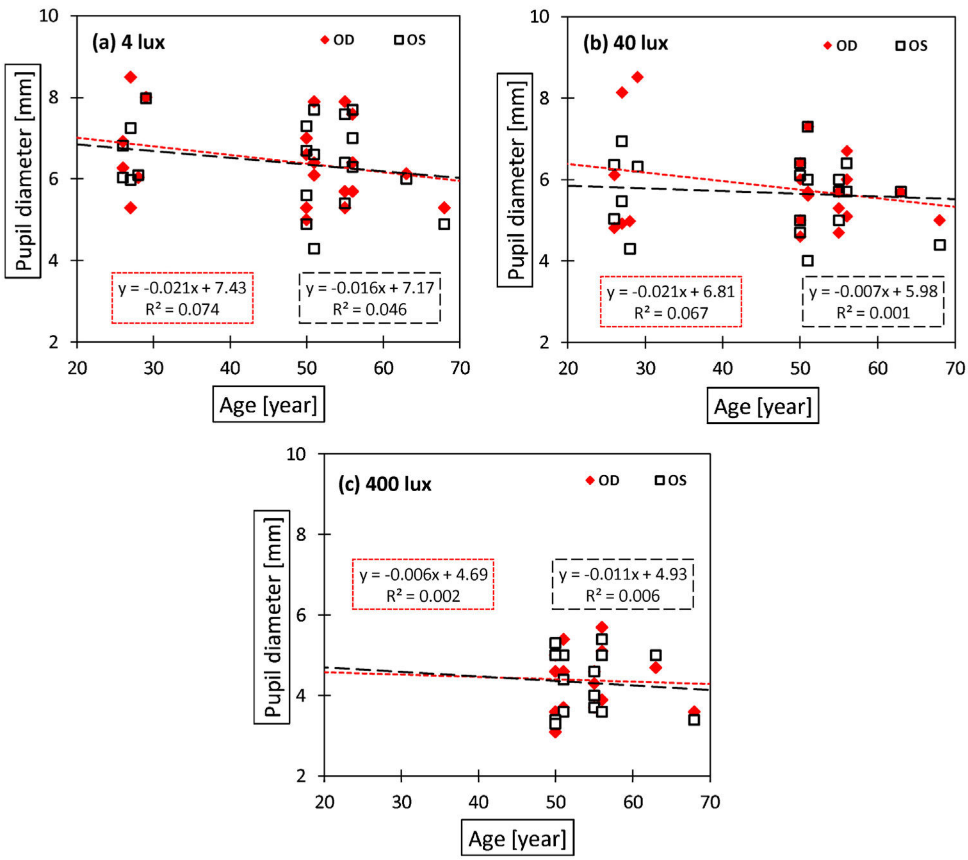

Figure 2 Dependency of pupil diameter on age under three levels of illumination. Data are fitted by linear regression. The slope of the regression line decreases as illumination increases (from *a* to *c*). Red diamonds show the right eyes and the empty squares show the left eyes. Red dotted lines and black dashed lines show linear regression lines for right and left eyes respectively.

The results are presented with the 95% confidence interval (95% CI) and the corresponding *p*-value. A *p*-value of less than 5% was considered statistically significant.

Results

Part 1

The average pupil diameter of both eyes of both groups for three levels of illumination is reported in Table 1. The values given are interindividual variations and have no association with the sensitivity of the measurements. Except for one subject, the pupil diameter was roughly the same under different levels of illumination in both eyes of each subject. It was no surprise that the effect of environmental illumination on pupil size appeared to be highly significant in all eyes ($p < 0.05$). The dependency of pupil size on age is depicted under three levels of environmental illumination (Fig. 2). The dependency of pupil size on age seems to be stronger under lower light intensities and decreases as illuminance increases. At the lowest illuminance level of 4 lux,

Table 1 Number of subjects, average pupil sizes and standard deviations.

Illuminance [lux]	Count	Average pupil diameter [mm]		SD [mm]	
		OD	OS	OD	OS
4	21	6.4	6.4	1.0	1.0
40	21	5.8	5.7	1.1	0.9
400	15	4.4	4.3	0.8	0.8

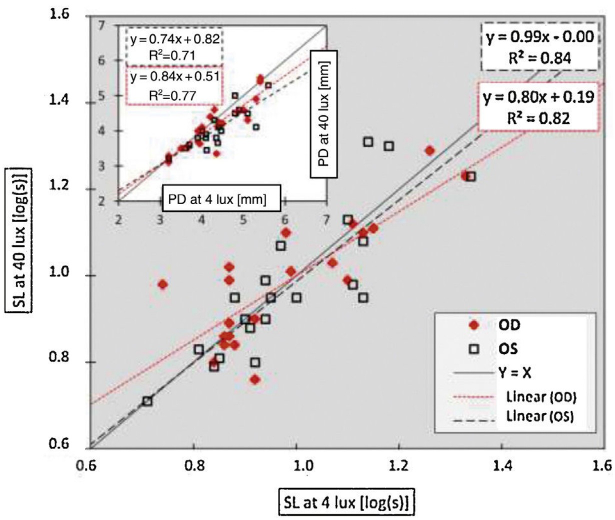

Figure 3 Mean pupil diameters (PD) of 20 subjects at 40 lux room illuminance (photopic condition) show high correlation with average pupil diameters at 4 lux room illuminance (mesopic condition). Ocular straylight measured under 40 lux background illuminance (photopic condition) shows high correlation with straylight under 4 lux background illuminance (mesopic condition). Red diamonds show the right eyes and the empty squares show the left eyes.

the average gradient is 0.018 mm per year and it lowers to 0.014 mm per year at the 40 lux and to 0.008 mm per year at the 400 lux room illuminance.

Part 2

The average pupil size during straylight measurement is calculated. The average values obtained under 40 lux illuminance are compared with those under 4 lux illuminance in Fig. 3. There are high correlations between the two sets of measurements for both eyes (*OD*: $R^2 = 0.77$, and *OS*: $R^2 = 0.71$). Straylight values of right and left eyes under 40 lux illuminance are plotted against those under 4 lux illuminance in the larger plot in Fig. 3. No statistically significant difference was found between scattered light under two light conditions, whereas high correlations were found between them in both eyes (*OD*: $R^2 = 0.82$ and *OS*: $R^2 = 0.84$).

No correlation was found between pupil size and corresponding straylight in both eyes under the two levels of illumination. With $\alpha = 0.05$, df = 18, and $r_{critical} = 0.514$ ($R^2 = 0.00$ for *OD*, and $R^2 = 0.07$ for *OS* at both illuminance levels). For the straylight difference between right and left eyes, we found means and standard deviations of 0.011 ± 0.084 log units under 4 lux illuminance and -0.006 ± 0.093 log units under 40 lux illuminance.

Fig. 4 shows the average pupil diameters of all 20 subjects collected in the last thirteen steps of straylight measurement at 4 and 40 lux environmental illuminance. Fig. 5 presents the estimated equivalent adaptation level of the straylight meter for all illuminance conditions, using the linear relationship between pupil diameter and room illuminance, over the course of the final phase (second half of the steps).

Discussion

We acknowledge the plausible limitations of this study due to a small sample size. The results in part 1, are in consistency with well-established knowledge. Pupil size, in a steady state, is a function of the corneal flux density[19] and age.[12,15] However, pupil size is influenced by more factors, such as field size and the number of eyes adapted.[16] The size of the pupil decreases linearly with age at all uniform illumination levels as suggested by Winn et al.[15] Our data also confirm what has been suggested by Winn et al.,[15] that under low levels of illumination, pupil size varies more with

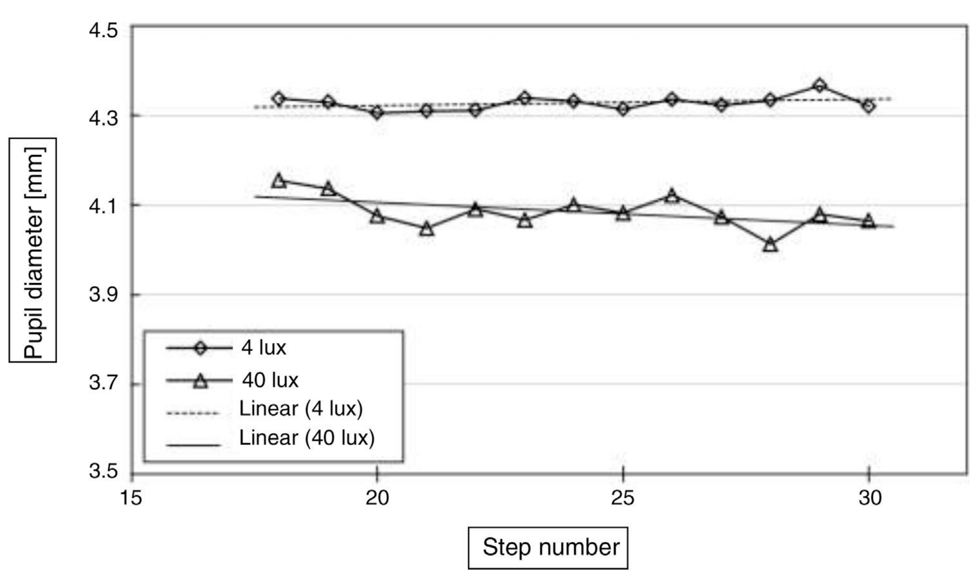

Figure 4 Average pupil diameter of all 20 subjects with normal eyes, obtained in the last 13 steps of straylight measurement at 4 lux (diamonds) and at 40 lux (triangles) room illuminances. The not-tested eye was exposed to mesopic and photopic room conditions.

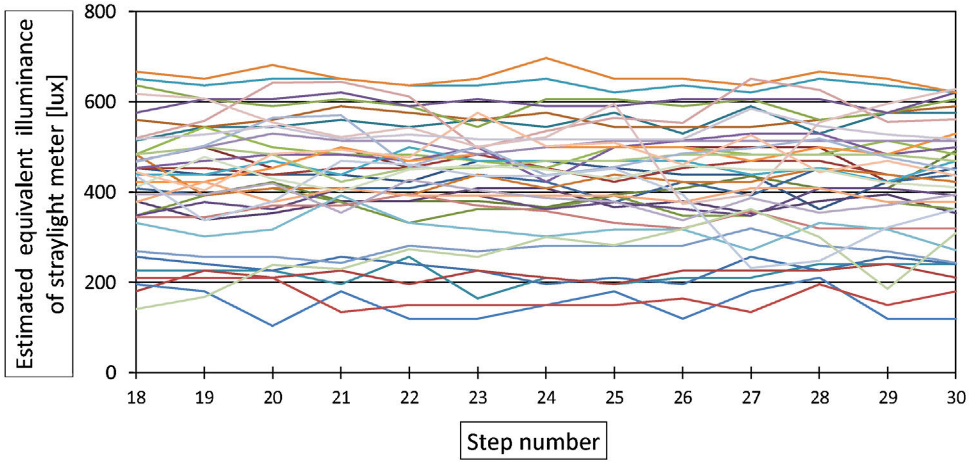

Figure 5 Estimated adaptation of C-Quant straylight meter during final phase of measurement for both eyes of 20 subjects. The eyes show an average value of 425 lux.

age. Left and right pupil sizes vary from low to intermediate illuminance in a highly similar manner which is expected according to consensual (indirect) pupillary response.

In the second part of the study, we studied the dependence of ocular straylight on environmental illumination. The average pupil diameter showed very little change from low to intermediate illumination conditions (Fig. 4). Franssen et al.[7] showed that straylight in normal eyes depends weakly on pupil size ranging from 2 to 7 mm diameter. We did not find a dependency between pupil size and straylight values using two light conditions. This can be understood as the recorded pupil values were largely in the middle range of the values reported by Franssen et al., and were moreover very close together. In the same study it was discussed that straylight is rather independent from environmental light intensity; pupil reflex experiments show that the headlights of an upcoming car at night-time, simulate a day-time condition which contracts the pupils to natural day-time sizes. Therefore, one can conclude that illuminance level and subsequently the pupil size are not crucial factors affecting the amount of induced ocular straylight measured with the C-Quant device. The data showed that the standard deviation of straylight difference between right and left eyes increased with age, albeit slightly. However, the average value of these differences and the standard deviations were small under either illuminance level. Both results are in agreement with findings by Montenegro et al.[20] They presumed asymmetrical lens aging of contralateral eyes as possible cause of the difference. During this psychometric determination of ocular straylight, almost independent from environment, the size of the pupil is determined by the straylight meter. The compensation comparison method used in the C-Quant has a photopic character, therefore, the eye is exposed to the stimulus that is quite brighter than the illuminance of the examination room. In addition, routinely, while measuring the study eye, the fellow eye is occluded. Our data also enabled estimating the adaptation of the C-Quant (Fig. 5).

For the 40 lux room illuminance condition, pupil size corresponded with 451 ± 122 lux room condition. For the 4 lux room condition the respective values are 399 ± 128. The eyes with estimated lower equivalent lux values were among those with relatively larger natural pupils at 400 lux room illuminance, and the eyes with estimated higher equivalent lux values were among the eyes with relatively smaller natural pupils at 400 lux room illuminance. With a large number of eyes estimating an average of 425 equivalent lux values, one can infer that the straylight meter sets the eye to a condition encountered with normal daytime room lighting.

Conclusions

We conclude that the illuminance of the examination room does not affect ocular straylight in normal eyes. In fact, the C-Quant test determines largely the size of the pupil. Thus, regardless of the lighting level, the straylight value obtained, is valid for normal photopic pupils.

Conflicts of interest

The Netherlands Academy of Arts and Sciences owns a patent on straylight measurement, with Dr. van den Berg as the inventor, and licenses that to Oculus Optikgeräte GmbH for the C-Quant instrument. None of the other authors has a financial or proprietary interest in any material or method mentioned.

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