Ocular axial length and straylight

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Complete List of Authors:	Christaras, Dimitrios; Athens Eye Hospital, Department of Research; University College London, Institute of Ophthalmology Rozema, Jos; Antwerp University Hospital, Department of Ophtalmology; University of Antwerp, Department of Medicine and Health Sciences Ginis, Harilaos; Athens Eye Hospital, Department of Research
Keywords:	Straylight, Intraocular Scattering, Myopia, Optics

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Dimitrios Christaras[1,2]*, Jos J. Rozema[3,4] and Harilaos Ginis[1]
[1] Department of Research, Athens Eye Hospital, Athens, Greece
[2] UCL Institute of Ophthalmology, University College London, London, England
[3] Department of Ophthalmology, Antwerp University Hospital, Faculty of Medicine, Antwerp University, Belgium
[4] Department of Medicine and Health Sciences, University of Antwerp, Antwerp, Belgium
*Corresponding author: d.christaras@athenseyehospital.gr

Purpose: Straylight refers to an optical phenomenon that takes places in the eye and leads to a deterioration of the retinal image. Past clinical findings suggest an increase of straylight with the eye's axial length, but the aetiology of the phenomenon was unclear. The purpose of this work is to demonstrate, through raytracing, simple geometrical optics, and the well-established inverse-angle square law for the angular distribution of straylight, why straylight increases when a myopic eye is corrected with spectacles.

Methods: The angular dependence of straylight is investigated using geometrical optics. An expression relating the eye's 2nd nodal point, the ocular axial length and the eye's straylight parameter S is found. Subsequently, using a model of the human eye, the location of the 2nd nodal point is computed using ray tracing for different axial lengths and refractive corrections. Finally, the results are compared against psychophysical data for the straylight parameter, corrected for the subject's age.

Results: When correcting axial myopia using spectacles, the eye's 2nd nodal point shifts towards the retina and away from the scattering plane, leading to an increase in straylight. Meanwhile, straylight should theoretically decrease in hyperopic eyes. Contact lenses keep the 2nd nodal point relative stable, leading to a very minor change in straylight with axial length. Our model has shown good agreement with previously taken straylight measurements in real eyes, explaining the observed change of straylight with ocular axial length.

Conclusion: We proposed an explanation for the underlying optical mechanism for the clinically observed increase of straylight with axial myopia, when corrected with glasses. Our model predicts that the increase can be as high as 0.12 log units for a myopic eye with 10 dioptres, which agrees with prior observations.

Keywords: Straylight; Intraocular Scattering; Myopia; Optics;

Introduction

Ocular straylight is a term describing elastic scattering of light, occurring mainly in the crystalline lens, the cornea and the ocular fundus, and directly affects the Point Spread Function (PSF) of the eye. [1–3] This influence is distinct from aberrations and diffraction at the pupil, exhibiting a much larger spatial range, affecting angles well beyond 2 degrees. [3,4] The visual effect of straylight is perceived as a decrease in the image contrast. [5,6] It has been shown that straylight is proportional to the fourth power of the subject's age, [7,8] but elevated scattering can also be the result of specific ocular pathogenies, such as corneal oedema and swelling, [9,10] or cataract. [11–13]

Scattering depends on a number of factors: the transparency of the ocular optics, and particularly the lens and the cornea, the wavelength, where medium range wavelengths scatter less than short and long, [14,15] and finally the dynamic range of the scene, with straylight being more pronounced when glare sources are present on a dark background. Moreover, the iris colour, and consequently the pigmentation of the eye, has been proven to have an effect on the amount of straylight. [16,17] Last but not least, clinical findings suggest a direct correlation between ocular biometry and straylight and particularly ocular axial length. [8] This last observation was the motivation behind this work.

There are two ways to measure straylight in-vivo in the human eye: psychophysically and optically. In psychophysical methods the subject has to perform a specific visual task and the amount of straylight is determined through their feedback. The direct compensation method is such a method that is also widely used in clinical practice [18,19] with repeatable results. [20] The optical methods do not require the subject's input; recently, an optical method called the optical integration method has been suggested for the measurement of straylight[3] that lead to a compact instrument. [21]

The purpose of this work is to examine the effect of axial length on straylight using an optical eye model and compare this model to psychophysical straylight measurements from an earlier study, [8] in order to provide an explanation for the clinically observed increase of straylight in myopia, as well as the decrease of the measured straylight after LASEK surgery. [22] The latter implies that the observed increased straylight in the myopic eye is not related to vitreous body defects.

The key observation behind this work is when using spectacles to correct for axial myopia, the eye's cardinal planes change; it is studied whether this change can explain the observed increase in the perceived straylight solely due to these changes in the geometrical characteristics of the eye.

Methods

Definition of the straylight parameter

Let $PSF_s(\theta)$ be the part of the point spread function of an eye associated to straylight. Assuming rotational symmetry, the PSF is approximated by the Stiles-Holladay empirical formula for glare [5,6]:

$$\frac{L_{eq}}{E_g} = PSF_s(\theta) = \frac{10}{\theta^2}$$

Where L_{eq} is the equivalent veiling luminance (cd/m^2) of a glare source that has illuminance E_g (Lux) and is at an angle θ with respect to the axis along which L_{eq} is measured. This can be written in a more general form as

$$PSF_s(\theta) = \frac{S}{\theta^2} \tag{1}$$

with S the straylight parameter, which is equal to about 10 for normal eyes and about 100 or more for a cataractous eye. Note that this function has a singularity at $\theta = 0$, making it unsuitable for approximating the PSF at small angles. Although more accurate formulas have been developed using psychophysical data, the above-mentioned inverse square angle law is remarkably accurate for angles between 3 and 30 degrees. [1,6]

From equation 1 if the PSF is known experimentally, straylight parameter S provides a robust (angle independent for angles over 3 degrees) number that can be used to report the severity of straylight. To calculate the straylight parameter the PSF must be first normalised to unity. Assuming only forward scattering and rotational symmetry this gives:

$$\int_0^{\pi/2} PSF(\theta)\, 2\pi\theta\, d\theta = 1$$

Units of PSF in this context are sr^{-1} and the straylight parameter can be calculated as $S = \theta^2 PSF(\theta)$ *(θ in degrees, S in degrees^2/sr).*

Straylight and axial length

Consider a single-surface eye model where all scattering occurs at a single scattering plane (blue surface shown in Figure 1) at the anatomical centre of the crystalline, hereafter referred to as scattering plane. This approximation is reasonable for the human eye as most scattering occurs at the crystalline lens and, to a lesser extent the cornea. In an emmetropic eye the 2nd nodal point is located approximately at the posterior surface of the crystalline lens, while in myopic eyes corrected with spectacles it is closer to the retina.

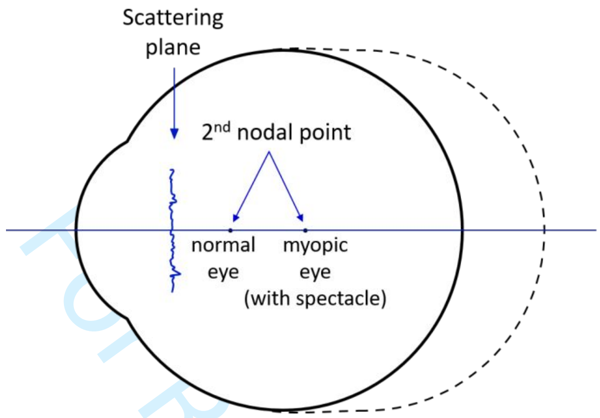

Figure 1. Schematic eye model showing scattering plane and the location of the 2nd nodal point.

Figure 2 shows a schematic overview of the eye, where L is the eye's total length, N the distance of the 2nd nodal point from the retina, θ the visual angle and L_o, N_o, θ_o for the special case for the emmetropic eye. For the spectacle-corrected myopic eye, light scattered at the scattering plane at an angle φ reaches the retina at a point that corresponds to visual angle θ originating from the eye's second nodal point.

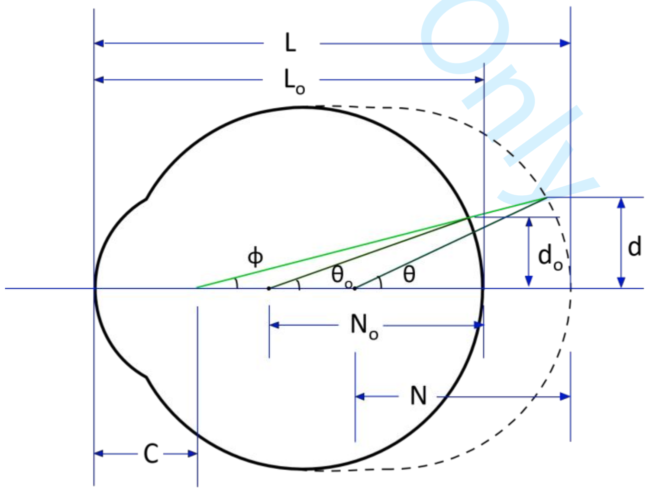

Figure 2. Angles and distances considered in the calculation.

Assuming the paraxial approximation, angles θ and φ can be written as follows

$$\theta = \frac{d}{N}$$

$$\varphi = \frac{d}{L - C}$$

Dividing the two equations we get.

$$\frac{\theta}{\varphi} = \frac{L - C}{N} \qquad (2)$$

where C the distance of the scattering plane from the anterior cornea. Now assume that light distribution at the retina for light scattered at the scattering plane is described by the following equation:

$$PSF_s(\varphi) = \frac{\alpha}{\varphi^2} \qquad (3)$$

where α a parameter expressing the total amount of scattering. Equations 1 and 3 express the same quantity in different coordinate systems and therefore

$$\frac{\alpha}{\varphi^2} = \frac{S}{\theta^2}$$

Solving for S and using equation 2 one gets

$$S = \left(\frac{\theta}{\varphi}\right)^2 \alpha = \left(\frac{L - C}{N}\right)^2 \alpha \qquad (4)$$

where α is independent of the axial length. Rewriting the latter for the emmetropic eye ($L = L_o$,$N = N_o$) we get

$$S_o = \left(\frac{L_o - C}{N_o}\right)^2 \alpha \qquad (5)$$

Dividing equations (4) and (5), applying the logarithm and rearranging gives

$$\log(S) - \log(S_o) = 2\log\left(\frac{\frac{L - C}{N}}{\frac{L_o - C}{N_o}}\right) = 2log\left(\frac{N_0(L - C)}{N(L_0 - C)}\right) \qquad (6)$$

This last equation gives the relative increase in scattering with axial length and is zero for the emmetropic eye.

Ray Tracing

The location of the second nodal point in myopia was calculated by ray tracing (ZEMAX) using a model of the human eye [23]. It was assumed that AL was accompanied by an elongation of the vitreous cavity, no changes in the cornea, the Anterior Chamber Depth (ACD) and lens thickness and the correction of the resulting refractive error was done by a thin lens placed 12 mm from the cornea (spectacles). The nodal point position was calculated for a range of values between -20D to 20D for the corrective lens. Correction at the corneal plane (contact lens) was also modelled.

An example of an emmetropic eye and a myopic eye corrected using spectacles can be seen in Figure 3. The scattered ray forms the same angle with the optical axis in both the emmetropic eye (left) and the myopic eye (right) but due to the displacement of the nodal point, it corresponds to a different visual angle.

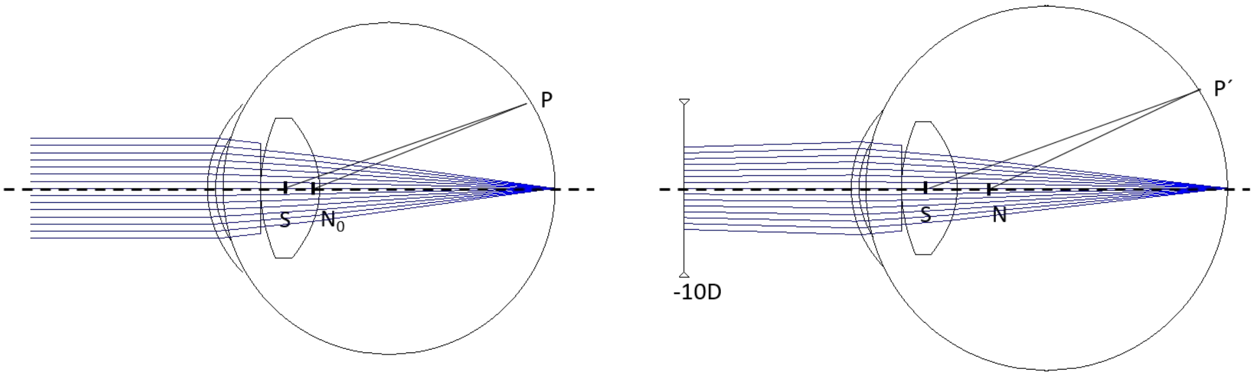

Figure 3. Simulated emmetropic eye (left) and myopic eye corrected using spectacles (right). S refers to the scattering plane, N to the nodal point and P the point of intersect of a scattered ray with the retina. For a ray that forms an angle of 30 degrees at the scattering plane, the emmetropic eye on the left will see it at 32.6 degrees whereas the myopic eye on the right at 38.6 degrees.

Straylight data

Straylight data were acquired psychophysically using the C-Quant instrument (Oculus Optikgerate; Wetzlar, Germany). The subject's refraction is corrected with the spherical equivalent using trial lenses at a distance of approximately 12mm, similar to the model used in the optical simulations. Axial length was measured using a commercial instrument for ocular biometry (IOL Master, ver. 2; Carl Zeiss Meditec, Jena, Germany). The dataset included measurements presented earlier [8] as well as additional data using the same instruments and conditions. In this study the current group only considers healthy people (while in the previous study 88 eyes of pre-refractive surgery patients were included). Straylight data were corrected for age following the model by Rozema et al[8]:

$$LOG(S) = LOG(S_0) - \left(P_1 + LOG10\left(1 + \left(\frac{A}{P_2}\right)^{P_3}\right)\right) \quad (7)$$

where the three parameters were $P_1 = 0.931$, $P_2 = 65$ and $P_3 = 4$. Straylight data were collected from a total of 389 volunteers (102 left and 287 right eyes), 158 males and 231 females. The maximum and minimum age was 81.1 and 8.5 years old respectively and the mean age was 45.2. The spherical equivalent error ranged from -8.75D to 5.8D with a mean of -0.6D. This study adhered to the tenets of the Declaration of Helsinki and received ethics committee approval (Ref. nr. 7/6/24). Signed informed consent was obtained from the participating subjects prior to their participation.

Results

The objective of the simulations was to determine the location of the 2nd nodal point for changes of the axial length of the eye. Figure 4 below shows the result of our simulations when axial defocus is corrected using spectacles and contact lenses. For spectacle correction the nodal point displacement is larger than for contact lenses. This is shown in figure 4 (left), where the distance of the nodal point from that of the emmetropic eye is plotted against the axial length of the eye.

Following the geometrical analysis in the section above, in order to the corrected $\log(S)$, the distance of the 2nd nodal point from the retina is needed. The displacement of the 2nd nodal point from the retina with axial length when corrected with spectacles and contacts is shown in figure 4 (right). A linear least-squares regression was used to fit the data and a corresponding equation was extracted. Note that the nodal point always moves at the direction of the retina, so for shortened eyes it lies closer to the cornea than for elongated eyes.

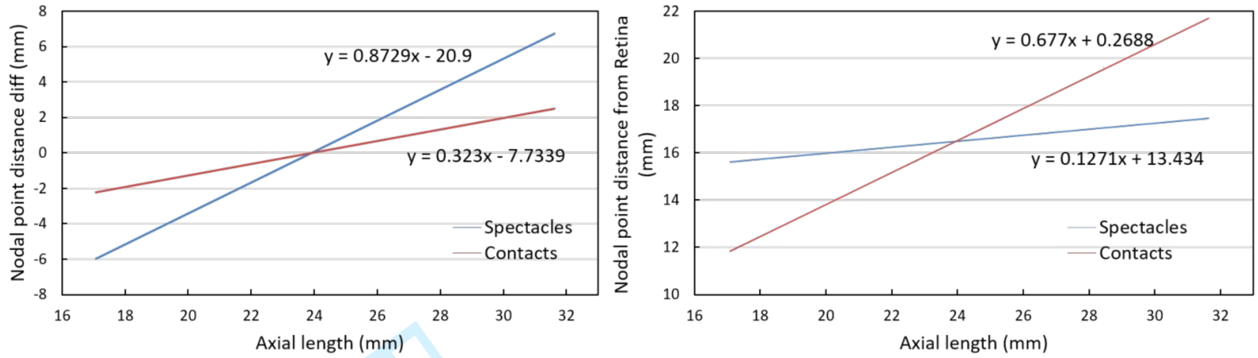

Figure 4. Position of the 2nd nodal point for eyes with different axial lengths corrected with spectacles and contact lenses relative to that of a 23.56 mm emmetropic eye (left). Distance between the 2nd nodal point and the retina in axial myopia corrected with spectacles and contact lenses (right).

From the simulations, the 2nd nodal point when spectacles are used follows the relation $N = 0.1271 \cdot L + 13.434$, where L is the ocular axial length. Plugging the latter into Equation 6, one gets

$$\log S - \log S_o = 2\log\left(\frac{(0.13 \cdot L_o + 13.43)(L - 6.05)}{(0.13 \cdot L + 13.43)(L_o - 6.05)}\right) \qquad (7)$$

where the scattering plane was assumed at the center of the lens, 6.05mm from the anterior cornea, and $L_o = 23.56mm$.

The age-corrected straylight data for 389 subjects are shown in figure 5. The black line in the figure represents the linear regression line describing the data and the red line is equation 8.

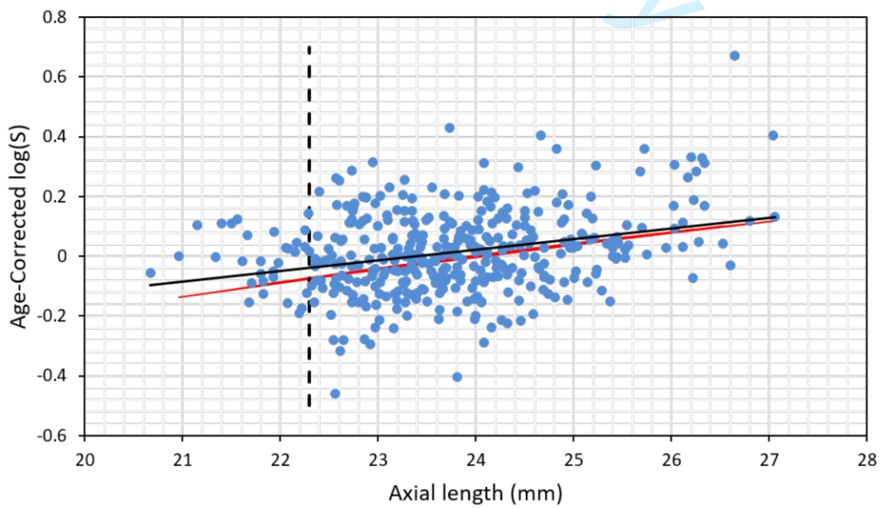

Figure 5. Experimental data (C-Quant) for S (expressed as log(S)) for different axial lengths. Black line is linear regression, red line is calculated from the model above. Dashed line at AL=22.3 depicts the axial length where the nodal point and the scattering plane coincide.

Discussion

Based on this analysis we conclude that the small increase of straylight observed in longer eyes can be explained on the basis of the different locations of the equivalent scattering plane and the nodal point of the eye. The analysis presented in this study assumes that the inherent scattering from the cornea and the crystalline lens are not affected by myopia.

Roughly one third of the subjects habitually wore contact lenses, some types of which are known to cause a significant increase in straylight.[24] Comparing the pre- and postoperative straylight in Lasik patients a significant decrease in straylight after the surgery was observed, independently of the habitual correction prior to surgery. [22]

It must be noted that the test field magnification (e.g. by the spectacles) would not explain this finding as straylight is rather independent of stimulus size for this angular range. The phenomenon described here can be actually seen as the relative magnification of the PSF with respect to the image.

This dependence of the measured straylight on the ocular axial length is by no means a measurement artifact; it has a true impact on the perceived straylight. A young healthy eye would have a straylight parameter log(S) of about 0.9 when measured with the C-quant instrument. [25] The same eye, if it were myopic, with an axial length of 27.7mm, or roughly -10D of defocus, the increase in straylight parameter would be 0.12 log units when corrected with spectacles, indicating a true functional increase of straylight. A recent study[26] on the effect of refractive correction on scattering supports that, albeit subtle, there is an increase in straylight when using negative powered refractive elements.

When contact lenses are used to correct for axial myopia, the eye's second nodal point gets displaced less than in the case of spectacles, leading to lower perceived straylight. As an example, the previous myopic eye of roughly -10D would have an increase of 0.022 log(S) when contact lenses are used compared to an increase of 0.12 log units for spectacles. The same mechanism could be a candidate to partially explain the observed change in straylight pre and post-LASEK [22] or in phakic IOL implantations. [27]

It is important to emphasize here that the model will not be suitable for shorter eyes. The reason is that, while for longer eyes the nodal point moves away from the scattering plane, for shorter eyes the nodal point approaches the scattering plane and eventually exceeds it. This means that for hyperopic eyes the corrected 2[nd] nodal plane will lie close by or even in front of the scattering plane: This would make the model inappropriate since the assumption that scattering happens at a single plane is no longer valid. This is partially reflected in fig. 5 where the model appears to deviate from the linear regression line describing the data (black line). The vertical dashed line in the figure indicates the axial length for which the nodal point and the scattering plane coincide, and thus determines the lowest value for which the model is valid.

Another important point is that in our model, we assumed that the eye's elongation was due to an elongation of the vitreous cavity. There is evidence, however, that other structures of the eye are affected: Axial length seems to be proportional to ACD and inversely proportional to lens thickness, [28] yet the vitreous cavity is the main structure that gets affected, with the ACD containing only a small fraction of the ocular elongation.

In the model, it was assumed that a change in the eye's axial length while keeping the corneal and lenticular power constant will lead to defocus. Each millimeter of axial displacement requires a spectacle correction of roughly 3 diopters to maintain focus. In the real human eye this is not always the case, since, despite the strong correlation between axial length and myopia, ocular biometry varies considerably between individuals. Consequently, two emmetropes can have significant differences in axial length, [29] such as e.g. the two extremes in our subject pool with axial lengths 22.2 mm and 24.6 mm. This corresponds to a difference in defocus of roughly 6 diopters in the model. For emmetropic eyes, or when defocus is corrected using contact lenses, the position of the 2nd nodal point has only a weak dependence on axial length, as seen in fig.4 (contact lenses - red line). For the two emmetropic axial length extremes for example, the relative displacement of the nodal point will be 0.65 mm, and the increase in log S will be roughly 0.03 log units. The presence of those extreme data points in our data pool is expected to have a small effect in our model due to the strong correlation of axial length and defocus.

Conclusion

Clinical findings have shown a direct relation between ocular axial length and retinal straylight, and more specifically an increase in straylight in myopic eyes. In this work, using geometrical calculations and optical simulations we suggested a physiological mechanism that could cause the aforementioned phenomenon; the displacement of the 2nd nodal point of the eye when the refractive error is corrected. Our model was in accordance with previously acquired psychophysical data of straylight in subjects with axial myopia.

Disclosure

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

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