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Introduction to straylight

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In an optical system, straylight refers to the light redirected by the process of light scattering out of an intended path defined by the optical design. Scattering originates from material inhomogeneities, *e.g.* particles, or surface roughness.[1] Scattering also takes place in the human eye.[2, 3] It results from optical imperfection of the eye optical media and creates a veil of light, which falls onto the retina and degrades contrast of the in-focus image.[2, 3] The CIE (Commission Internationale d'Éclairage) defined straylight as the means of proper quantification of disability glare.[4] It corresponds to the outer (>1°) part of the functional Point Spread Function (PSF) (**Figure 1**) and is expressed by means of the straylight parameter (s):

$$s = \theta^2 \times PSF(\theta) \quad [deg^2/sr]$$

at a θ distance from the straylight source.[4] In a clinic, however, most often straylight is presented logarithmically as log(s).

Straylight is a separate, from visual acuity (VA) and contrast sensitivity (CS), domain of the functional PSF (**Figure 1**), thus standard ophthalmic tests cannot be used for its assessment in the eye.[3] In response to the need of a clinical instrument, new devices have been proposed that are designed based on the PSF approach.[3, 5-7] One such a device is the C-Quant straylight meter (Oculus Optikgeräte GmbH, Germany), which follows the CIE standard, using a psychophysical approach to directly assess the functional PSF at 7-degree scatter angle,[3, 6] and is the subject of this thesis. The HD Analyzer (Visiometrics SL, Terrassa, Spain) is an instrument that uses a double-pass method for the PSF assessment of the eye.[5, 7] This apparatus, however, measures the PSF in an angular range of minutes of arc.[5, 7] Its validity for scatter assessment has been seriously criticized.[7] A new double-pass approach has been proposed that may be free of some of those limitations,[8] but a clinical instrument is yet to be introduced.

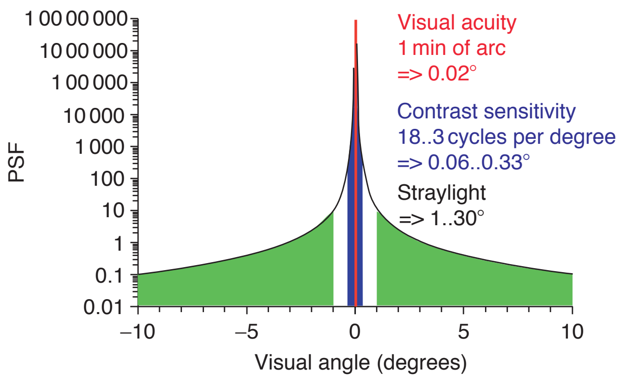

Figure 1. Functional Point Spread Function (PSF) of a normal eye. The PSF can be used to quantify visual performance in terms of: visual acuity (red peak), contrast sensitivity (blue area) and straylight (green area) *(Encyclopedia of the Eye, 2010).*

C-Quant straylight meter

The PSF approach, as defined by the CIE standard, is applied in the C-Quant straylight meter (**Figure 2**).[2, 3, 6, 9]

The C-Quant assesses the straylight parameter (presented as log[s]) by means of the psychophysical compensation comparison method.[6, 9, 10] This methods works as follows. A C-Quant test screen (**Figure 3**) consists of a flickering (in black and white) ring that surrounds the test field and serves as a straylight source.

Figure 2. C-Quant straylight meter.

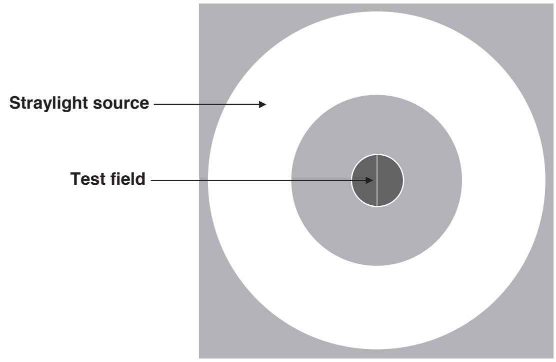

Figure 3. C-Quant test screen.

The test field is divided into 2 halves. In both halves flickering results from light scattering in the eye (part of the straylight source is scattered towards the fovea). But in one, randomly chosen half, counter-phase light (called compensation light) with different modulation depths is added. In the course of the C-Quant test, a patient decides which of the 2 halves flickers stronger and presses a respective push button (the left/right button correspond to the left/right half) to provide a response. The difference between the 2 halves is compensated by compensation light of a known value. After pressing the button, another amount of compensation light is added and at a certain moment both halves flicker at more or less the same intensities. This point defines the straylight value, by the equivalence principle. Although, at this point a difference may be difficult to see, the subject must guess and press one push button. This is a well-established psychophysical principle, called a 2-alternative forced choice method. Based on the subject's responses a psychometric curve is fitted with the minimum giving the sought straylight value.[6, 9, 10]

The C-Quant has proved repeatable and reliable in clinical studies.[11, 12] This instrument provides a functional straylight parameter that is subjectively almost as important as VA for overall appreciation of visual quality. It has been shown that a 0.1 increase in log(s) is close in subjective importance to a loss of 1 line on the logMAR scale.[13]

Straylight in the phakic eye

Four major anatomical sources of ocular straylight can be found in a young normal eye (**Figure 4**).[2, 3, 14]

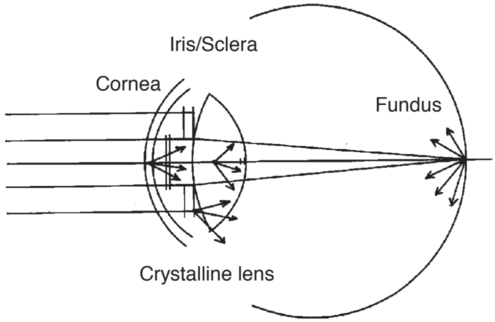

Figure 4. Sources of straylight in a healthy eye *(Encyclopedia of the Eye, 2010)*.

The cornea and the crystalline lens account for 2/3 of total scattering (1/3 each), the remaining 1/3 results from fundus reflectance and light transmittance through the ocular wall.[2, 3, 14] This proportion may, however, change due to aging of the crystalline lens.[2, 3, 14-16] It has been shown that ageing is an important factor in straylight of the eye. Most recently, a large population study has assessed straylight in over 2,000 healthy eyes introducing a new norm of straylight in normal phakic eyes (**Figure 5**).[16]

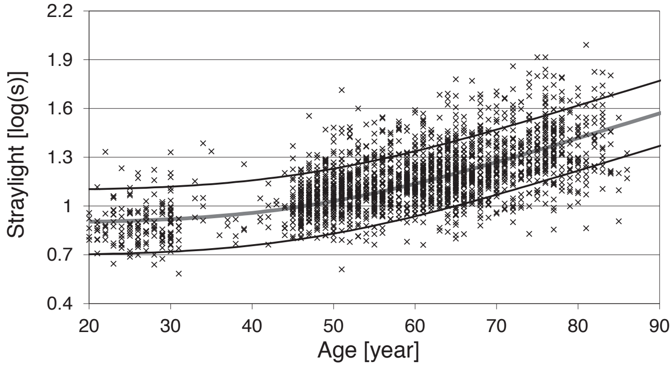

Figure 5. Straylight as a function of age in normal phakic eyes (*Van den Berg et al. Am J Ophthalmol 2007;144*).

Figure 5 shows a clear straylight increase with age in normal eyes, and this relationship was used to formulate a CIE standard for the PSF.[3, 4, 14-16] The CIE standard contains formulas of different levels of complexity. One such formula is:

$$PSF = \frac{10}{\theta^3} + \left(\frac{5}{\theta^2} + 0.1\frac{p}{\theta}\right)\left[1 + \left(\frac{Age}{62.5}\right)^4\right] + 0.0025p$$

where θ is the visual angle and p is a parameter for the degree of pigmentation of the eye.[2, 4, 11, 16, 17] The p parameter depends on iris color (pigmentation) and ranges from 0.00 to 1.21, *e.g.* for an average Caucasian eye p=1.[14] **Figure 5** and the model also show that even a young, healthy eye scatters light at a level of log(s)=0.9, and it accounts for (approx.) 5% of the incoming light.[14] Straylight remains at this level until age 40, then it gradually increases to be doubled at the age of 65 years.[14, 16] A model prediction of straylight for a 35-year-old and 65-year-old eye, and a cataractous eye are presented in **Figure 6**.

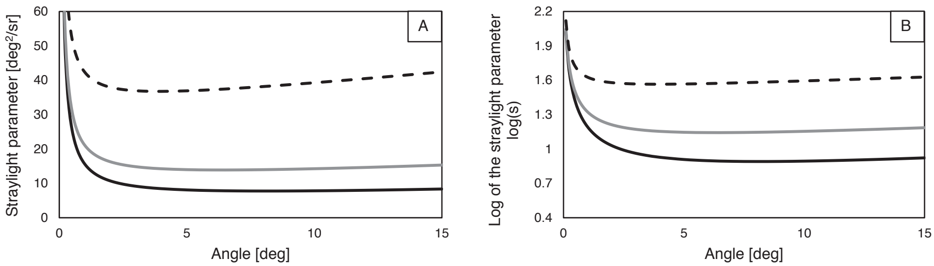

Figure 6. CIE standard for the Caucasian eye presented as the straylight parameter (A), and clinically as log(s) (B). The black and gray solid lines refer to a normal eye at aged 35 and 65, respectively. The black dashed line indicates straylight of a cataractous eye that was calculated as an equivalent to that of a 95 year-old eye.

Several pathological conditions have been associated with straylight elevation.[3, 17-31] Increased straylight results in disability glare, which may be described by patients as difficulties while driving at night (as caused by headlights of approaching cars) or against a low sun.[2, 3, 32] Straylight can also be related to such complaints as hazy vision, problems with face recognition and decreased color sensitivity.[2, 3, 32] **Figure 7** illustrates high and low straylight levels.

Although a young crystalline lens shows very low straylight (*e.g.* for a 20-year-old lens it is 0.39 log[s]),[14] aging process and lens-related disorders, such as (early) cataract, cause ocular straylight to increase.[3, 17, 19, 24] The literature has shown that all cataract types are associated with straylight elevation. However, significant differences between the types exists,[3, 17, 19, 24, 33] as a mean straylight increase of 1.05 log(s), 1.36 log(s) and 1.54 log(s) was found in patients with cortical, nuclear and posterior subcapsular cataract, respectively.[33] Although the CIE standard is mostly used for age-based prediction of straylight of the normal eye, the same formula can also be used to model cataract (**Figure 6**). This can be understood as early aging of the crystalline lens, *e.g.* straylight of best 95-year-old lenses (log[s]=1.52) is comparable to the average effect of cataract found in a population

Figure 7. Visualization of a (A) low and (B) high (1.47 log[s]) straylight level *(Encyclopedia of the Eye, 2010).*

study.[3, 14, 15, 19] The cornea may become an important source of ocular straylight, as loss of transparency or integrity yields a significant straylight increase. Most of the corneal dystrophies such as crystalline[18, 20] or Fuch's dystrophy[23, 25, 29] result in straylight elevation. For instance, a 20-fold straylight increase, as compared to straylight of the healthy eye, has been reported in most severe cases.[18, 20] Significantly increased straylight (a 2.5-fold increase) has also been found in patients with keratoconus as compared to normal (control) subjects.[30] Although the effect of the vitreous of a healthy eye on straylight is minute, vitreous turbidity (*e.g.* floaters) can give rise to functionally important straylight elevation, and that is 1.54 log(s) on average.[28]

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