Chapter 5

Degradation of visual performance with increasing levels of retinal stray light


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ABSTRACT

PURPOSE: To quantify the effect of induced stray light on halo size, luminance threshold and contrast sensitivity.

METHODS: Retinal stray light was induced in five healthy subjects using different photographic filters. The stray light induced ranged from levels observed in intraocular lenses (IOLs) with glistenings to cataract level, and was measured both psychophysically with commercially available instruments and on an optical bench. The visual impact was measured for halo size, luminance detection threshold, and contrast sensitivity with and without a glare source.

RESULTS: The amount of retinal stray light induced by the different filters was similar when measured, using the psychophysical method and the optical bench method. Stray light levels mirroring a typical glistening case causes the halo size to increase by 21%, the luminance detection threshold to increase by 156%, and contrast sensitivity to decrease by 10% to 21% dependent on spatial frequency and presence of a glare source. The visual impact percentages for a typical cataract case are respectively 76%, 2130% and 30% to 49%. In the presence of a glare source, contrast sensitivity losses were larger and shifted to lower spatial frequencies.

CONCLUSIONS: Low levels of retinal stray light can cause significant increases in halo sizes, elevations in luminance detection thresholds and reductions in contrast sensitivity whether or not a glare source is present. The visual effect for a severe glistening case can be comparable to a mild cortical cataract case.
Introduction

Some of the most significant visual disturbances affecting cataract patients are caused by retinal stray light. Nevertheless, the visual impact of relatively low levels of stray light can be hard to quantify, as it does not cause a drop in visual acuity. The diagnoses of these visual problems are most commonly made using slit lamp exams of potential sources of stray light. Direct psychophysical measurements of stray light levels are available as commercial instruments. However, the visual impact of measured stray light with these instruments is still not well understood. The level of retinal stray light determines the level of disability glare and can be a reason for persistent visual complaints [1]. Scatterers in the crystalline lens or micro vacuoles present in the optic body of an intraocular lens (IOL) are sources that can cause retinal stray light. The resulting disability glare may constitute visual complaints like hazy or blurry vision leading to cataract extraction or IOL explantation [2, 3]. The stray light behavior of the eye as a function of age, pigmentation, and angle have been studied extensively [4-6], and the influence of age can be used to illustrate the effect of stray light in the presence of a cataract [6]. Furthermore, the stray light behavior of micro vacuoles or glistenings has been described in the past for four different types of IOLs [7]. However, retinal stray light is currently not routinely measured in clinical practice as a way to diagnose cataract or glistenings; the opacification of the crystalline lens or the micro vacuoles in the optic body are routinely only assessed in a slit lamp exam. This exam subjectively illustrates the effect of backward scattered light from the opacities in the crystalline lens or the micro vacuoles in the IOL optic, while it is the forward light scattering distributed over the retina that determines the visual impairment. Therefore, there is a need to relate visual complaints of patients and the corresponding slit lamp exam to understand visual performance measures and clarify the visual impairment caused by retinal stray light.

In clinical practice, vision is assessed most commonly with visual acuity (VA) and occasionally with contrast sensitivity tests. Cataract patients may have uncompromised VA but may still complain of poor vision [8] limiting the clinician’s ability to accurately diagnose the complaints. Visual acuity and retinal stray light are known to be independent quantities and measures [9] because they assess different aspects of vision. VA is a measure of the foveal image quality of high contrast details and therefore does not change with increasing stray light until excessive levels are reached, whereas retinal stray light determines the level of disability glare. Disability glare can be defined as the contrast reduction of a visual scene due to the retinal veiling luminance induced by a glare source in the field of view. Several studies found decreased contrast sensitivity for all, or part of, the spatial frequencies reported in the presence of cataract [8, 10-14]. The level of decrease in contrast may depend on the cataract morphology investigated: cortical, nuclear or posterior subcapsular [10-13]. Similarly, five studies have shown decreased
contrast sensitivity for the higher spatial frequencies when glistenings are present in the body of the IOL optic [15-19] and two studies were non-conclusive [20, 21]. Despite these studies, general understanding of the implication of these relatively low levels of retinal stray light on visual function is limited and uncertain even in cases when retinal stray light is measured and quantified [2, 21-23]. Therefore, in this study, an improved contrast sensitivity test with and without the presence of a glare source and a luminance detection threshold test are used to create quantifiable visual performance measures of the impact of retinal stray light. Halo size is chosen as another visual performance measure because its clinical significance is intuitively understandable. In daily life, even low amounts of scatter may cause significant visual problems if glare sources are present. In this investigation, we systematically induced low degrees of scatter, typical of the levels found for glistenings and moderate degrees of cataracts, and measured the visual effects with and without the presence of glare sources. The objective of this study was to determine the visual consequences of scatter by relating varying levels of stray light to several measures of the quality of vision.

Methods

This section describes all methods and materials used to induce and to measure stray light, as well as the methods used to determine the relationship between stray light and visual performance.

Subjects

In this investigation, measurements were performed on five right eyes of five healthy subjects between the ages of 28 and 53 years at the Royal Institute of Technology, Stockholm. Four subjects were emmetropic and one habitually wore contact lenses (-2.50 D). The study conformed to the tenets of the declaration of Helsinki and was approved by the regional ethics committee in Stockholm, Sweden (2013/1433-31/1). Written informed consent was obtained prior to the start of the study.

Stray light and photographic filters

The scatter parameter $s$ as function of angle $\theta$ is defined as $s(\theta) = \text{PSF}(\theta) \times \theta^2$, where PSF is the point spread function [5]. The PSF describes the light intensity distribution over the retina and declines steeply with angle $\theta$. To record and distinguish visual effects in the periphery, the PSF is multiplied by angle squared resulting in the scatter parameter describing relative light power distribution over the retina. Within the central one degree, the PSF is dominated by defocus or wavefront aberrations of the eye that are determined by the shape and relative position of the ocular optics. The scatter parameter is an important and visually relevant measure of performance for angles larger than one degree, where the PSF is dominated by ocular scatter sources like cataract or glistenings.
This part of the PSF can also be described by photometric quantities as the ratio between veiling luminance on the retina and illuminance of the glare source at the pupil plane.

In this experiment photographic filters are used to induce stray light of varying levels on the retina of the eyes of the subjects. These filters were chosen to reflect the levels of scatter by varying ocular conditions. In order to cover the range of values that would represent stray light caused by glistenings the scatter parameter should range from $s=3$ deg$^2$/sr to $s=10$ deg$^2$/sr [7] and for cataracts the scatter parameter should range from $s=10$ deg$^2$/sr to $s=30$ deg$^2$/sr [9,24]. Three photographic Black Pro-Mist® (BPM) filters BPM¾, BPM1 and BPM3 (The Tiffen Company, NY, USA) were chosen from a range of filters based on the values of scatter that were induced by these filters. The stray light of the filters were characterized using an optical bench based technique that has been described in detail previously [25]. This optical bench method measures the stray light parameter, $s$, as a function of angle $\theta$. Retinal stray light at an average angle of 7 degrees was measured using the compensation comparison method implemented in the C-quant (Oculus, Germany) [1]. In addition to the standard setup, a C-quant was modified by extending the distance of the eye piece so that the stray light could be measured for an average angle of 2.5 degrees. The C-quant provides in vivo measures of the logarithm of the stray light parameter $\log(s)$.

**Halo Size**

The halo size was measured using the Rostock Glare Perimeter [26]. In the Rostock Glare Perimeter, a small square marker is detected as it moves outwardly from a central glare source. The subject fixates on the glare source, and indicates when the marker becomes visible, which will reproduce the psychophysical halo radius using the method of adjustment. The square marker has a side length of 0.1 degrees, a luminance of 25 cd/m$^2$ and the subject sits 3 m away. The glare source has an illuminance of 0.4 lux at the eye, and the procedure is repeated three times in 12 different meridians. The perceived retinal halo is constructed by connecting all measurement outcomes from each meridian and averaging the halo radius $R$ to determine $\log(R)$ for each subject and each stray light level.

**Luminance threshold**

The luminance detection threshold was determined using a modified Rostock Glare Perimeter with a novel procedure developed for this study. In this procedure, a two alternative forced choice method was used to determine the detection threshold at a fixed angular distance to the glare source. The task of the subject was to indicate the location of the 0.1 degree square stimulus, which appeared for 0.5 seconds above or below the glare source. The luminance threshold of the marker was determined by an
adaptive Bayesian algorithm and 50 trials were used to find the luminance level at which the subjects would indicate the correct location of the marker with 75 % probability. The procedure took less than two minutes. The subject was located 2.5 meters from the central glare source which had an illuminance of 0.75 lux at the eye. The procedure was repeated three times for each subject and condition, and the logarithm of the luminance, log (L) at the threshold was used as the outcome measure.

**Contrast Sensitivity**

The complete Contrast Sensitivity Function (CSF) was measured in 100 trials with the quick CSF method [27] using a calibrated CRT screen displaying Gabor gratings with a mean luminance of 48 cd/m². The CSF was also measured with a glare source placed in the horizontal nasal field at 2.5 degrees and 7 degrees respectively with an illuminance of 12 lux at the eye. A range of contrast sensitivity levels was determined starting from a spatial frequency of 1 cycle per degree (cpd) with a sampling rate of 0.0085 log (cpd), and the area under the contrast sensitivity curve log (AULCSF) was determined for each subject and stray light level. The procedure took less than four minutes for one condition.

**Procedure**

All five subjects were measured over a period of several days, in randomized order with and without the three photographic filters placed in a trial frame using all of the methods described.

**Analysis**

For each subject, the induced stray light of the filters was calculated by subtracting the measured stray light level without any filter from the stray light level with each filter. The average measured degree of induced stray light for all subjects was compared to the optical bench measurement result for each filter of the linear stray light parameters for 2.5 degrees and 7 degrees. The stray light levels were then correlated with each visual outcome for the angles of 2.5 degrees and 7 degrees. Because the same subject was measured with different filters, the within subject data points are interdependent. Therefore, the relationship between all stray light outcomes and visual performance outcomes were fit using the partial least squared (PLS) method Modde 5, (Umetrics AB, Umea, Sweden) to isolate the effect of stray light from any subject dependent effect. The confidence level is set to 95%.

Results were compared to a typical baseline stray light value, which is 1.1 log(s) for a 70 year old healthy or a typical pseudo-phakic subject [9]. To determine the stray light effect caused by glistening and cataract on the baseline stray light level, the induced stray light level of an average glistening case of s=5 deg²/sr [3,7] and a moderate cataract case of s=20 deg²/sr [24] were then added to the baseline stray light level. These induced stray
light values in log(s) were used to calculate the effects of a typical glistening case and a moderate cataract case on all measured visual performance outcomes. A night driving scene as perceived by a typical pseudo-phakic case was used to simulate the visual impact for a typical glistening case, a severe glistening case (s=9 deg\(^2\)/sr) [7] and a mild cortical cataract case (s=11 deg\(^2\)/sr) [24]. The headlights were assumed to be glare sources giving an illuminance of 0.6 lux with an average background luminance of 1 cd/m\(^2\). The images themselves have a size of 20°. To the image, we have added the veiling luminance produced by glistenings or cataract. For the cataract case log(s) is assumed to be constant over the field because the size of the scatterers is comparable to the wavelength of light while for the glistenings case the stray light profile as measured by van der Mooren et. al. [7] has been used, with peaks at 2.5° and 15°. The glistening stray light profile is angle dependent because the micro vacuoles have sizes larger than the wavelength of light, ranging from 2 to 40 micrometer [7].

**Results**

**Stray light**

The stray light characteristics measured on the optical bench were comparable to the average induced stray light levels as measured with the extended and standard C-quant in the five subjects (figure 1). This implies that the induced retinal stray light is purely an optical effect caused by the inhomogeneity of the filter. As expected, the stray light level of the filters at 2.5 degrees is higher than that measured at 7 degrees. Furthermore, it can be seen that the photographic filters induce stray light levels ranging from 3 to 30 deg\(^2\)/sr and that therefore the filters are able to simulate the stray light effects caused by glistenings in IOLs and by cataract cases.

![Figure 1](image)

*Figure 1* Average induced retinal stray light measured in five subjects with (left) the extended C-Quant and (right) the standard C-Quant compared to optical bench measurement results for each filter. Error bars indicate standard deviations.
To illustrate the effects caused by a typical glistening case and a moderate cataract case, the induced stray light in these cases were added to the baseline stray light level and plotted against the baseline level (Figure 2). It is clear that the induced effect on stray light is larger for subjects having lower baseline stray light values. For a typical pseudo-phakic subject or a 70 year old healthy subject the baseline retinal stray light level is 1.1 log(s), and will increase by 0.15 log(s) for a typical glistening case and by 0.4 log(s) for a moderate cataract case (figure 2).

Figure 2 Retinal stray light effects of typical glistening case and moderate cataract case as a function of baseline stray level.

The simulated images (figure 3) show the potential impact for a typical and severe glistening case and a mild cortical cataract case. The larger the induced stray light level, the less visible is the crossing pedestrian because of the increasing halo of the oncoming car. The severe glistening case resembles the mild cortical cataract case.
Degradation of visual performance with increasing levels of retinal stray light

Figure 3 Night driving scene perceived by (top left) a typical pseudo-phakic case and (top right) typical pseudo-phakic glistening case, and (bottom right) severe pseudo-phakic glistening case and (bottom right) mild cortical cataract case.

Partial Least Squares (PLS) Fitting

The PLS fit showed that for all visual test outcomes there were no fundamental interaction between the observed stray light levels and the subjects tested. This also explains why the linear regression yielded similar correlation results as obtained with the PLS method. The reported slopes were calculated using the standard linear regression method.

Halo Size

The measured halo size was highly correlated with the level of stray light at both 2.5 degrees and 7 degrees ($R^2=0.75$ and $R^2=0.79$ respectively) (figure 4). The halo size increased with a slope of 0.55 log units for one log(s) unit increase in stray light at 2.5 degrees. For one log(s) unit increase in stray light at 7 degrees the halo radius increased with 0.61 log units. This means that the halo size measurement is half as sensitive as the stray light measurement regardless of the angle for which the stray light is determined. Recalculated, this means that for a 0.15 log(s) stray light increase at 2.5 degrees (typical glistening case), the halo radius increased by 21% and for 0.40 log(s) stray light increase at 7 degrees (cataract case) the halo radius increased by 76%.
Figure 4 Halo size as function of stray light level (left) at 2.5 degrees, and (right) at 7 degrees for five subjects.

**Luminance threshold**

The measured luminance threshold as a function of stray light level at 2.5 degrees and 7 degrees had a high correlation (R²=0.73 and R²=0.71 respectively) (figure 5). The luminance threshold increased with a slope of 2.72 log units for one log(s) unit increase in stray light at 2.5 degrees. For one log(s) unit increase in stray light at 7 degrees the luminance threshold increased with a slope of 3.73 log units. The luminance threshold measurement is therefore almost four times as sensitive as the stray light measurements at 7 degrees. For a 0.15 log(s) stray light increase at 2.5 degrees (typical glistening case), the luminance threshold increased by 156 % and for a 0.4 log(s) stray light increase at 7 degrees (cataract case) the luminance threshold increased with 2130 %. This illustrates the detrimental effect of cataract by showing that there is a more than 20 fold loss in luminance threshold for a moderate cataract case.

Figure 5 Luminance thresholds as function of stray light level (left) at 2.5 degrees, and (right) at 7 degrees for five subjects.
Contrast Sensitivity

For all measured conditions, the area under the contrast sensitivity function $\log(AULCSF)$ was highly correlated with induced stray light for each subject but the baseline level varied between individuals. This trend is displayed by the average slope of $\log(AULCSF)$ of all five individuals as function of stray light level. For one log(s) unit increase in stray light at 2.5 degrees, $\log(AULCSF)$ without a glare source and with a glare source located at 2.5 degrees decreased by 0.48 to 0.87 log units respectively with high correlation ($R^2=0.70$ and $R^2=0.83$ respectively)(figure 6).

For one log(s) unit increase in stray light at 7 degrees, $\log(AULCSF)$ without and with a glare source located at 7 degrees decreased by 0.59 and 0.67 log units respectively with a high degree of correlation ($R^2=0.78$ and $R^2=0.64$ respectively)(figure 7). The retinal stray light effect on contrast sensitivity (CS) was largest for a glare source located at 2.5 degrees.

Figure 6 Area of contrast sensitivity (AULCSF) as function of stray light level at 2.5 degrees for (left) without glare source and (right) with glare source at 2.5 degrees for five subjects.

Figure 7 Area of contrast sensitivity (AULCSF) as function of stray light level at 7 degrees for (left) without glare source and (right) with glare source at 7 degrees for five subjects.
The effects of a typical glistening case and a cataract case on the contrast sensitivity as a function of spatial frequency follow the same trends, however the degree of severity differs (figure 8). The effect of increased stray light on CS without a glare source is largest for spatial frequencies between 7.5 cpd and 25 cpd. When stray light is elevated by the level associated with a typical glistenings case the CS for this spatial frequency range decreases between 14% and 20%, and when stray light is elevated by the level associated with a moderate cataract case the CS for this spatial frequency range decreases between 30% and 42%. The effect of stray light on CS with a glare source present is largest for spatial frequencies between 1.5 cpd and 10 cpd. When stray light is elevated by the level associated with a typical glistening case the CS for this spatial frequency range decreases between 10% and 21%, and when stray light is elevated by the level associated with a moderate cataract case the CS for this spatial frequency range decreases between 34% and 49%. CS was reduced by a maximum of 20% at 15 cpd for a typical glistening case and 42% at 18 cpd for a cataract case. These percentages are 21% at 3.5 cpd and 49% at 3 cpd respectively when contrast was measured in the presence of a glare source. The presence of a glare source further decreases the CS when stray light levels are elevated. Additionally, the presence of the glare source shifts the CS decrease to the lower spatial frequency range.

**Figure 8** Baseline contrast sensitivity (solid blue line), contrast sensitivity for stray light elevated to a typical glistening level (dotted gray line), and contrast sensitivity for stray light elevated to a cataract case (dashed red line). The left graph shows contrast sensitivities without glare source and the right with a glare source present at 2.5 degrees.
Discussion

The aim of this study was to develop a better understanding of the functional effects of increased retinal stray light caused by various visual disruptions (cataracts, glistenings) on visual performance. We found a significant and consistent impact of stray light on all three visual tests for all subjects. Retinal stray light, induced with photographic filters and measured subjectively by compensation comparison with the C-Quant, corresponds remarkably well with stray light as measured on the optical bench. This suggests that perception of retinal light scatter is not limited by the retinal structures and image processing in the subsequent visual pathways but is for the most part defined by the optical light scatter distribution over the retina. These findings support the fact that the tail of the PSF can be described in photometric terms as the ratio between the retinal veiling luminance and the illuminance of the glare source at the pupil plane. Comparable measurement results have been found in earlier studies for glare sources located at an average angle of 7 degrees for filters BPM1, BPM2 and BPM3 [24], and these findings are corroborated by the current study for an angle of 2.5 degrees and for lower light scatter levels as represented by the filter BPM¾. The induced retinal stray light values studied, range from levels comparable to a moderate degree of cataract [9, 24] down to levels comparable to that found for IOLs with glistenings [7] as well as for two explanted IOLs having stray light values of 4 and 6 deg²/sr for angles at 2.5 degrees [3]. These stray light levels are lower than the severe glistenings case that had 9 deg²/sr and showed comparable effects to the mild cortical cataract condition in the image simulations of the night driving scenes. This suggests that stray light caused by glistenings can have comparable levels as caused by cataract.

The stray light effects induced by glistenings are predominantly distributed around two retinal peaks located at an angle of 2.5 and 15 degrees [7]. This means that the standard C-quant is not the most suitable instrument to detect the effects of glistenings, as it operates with a glare source located at an average angle of 7 degrees. The extended C-quant used in this study, that performs stray light measurements at an average angle of 2.5 degrees is therefore a better instrument for measuring these effects. Another method used to measure the stray light from glistenings is the Scheimpflug technique [22, 23] which quantifies backward light scatter. However, the perception by the patient depends on the forward (retinal) light scatter. Forward stray light levels can be as much as 300 times larger than that of the measured backward scatter due to the fact that glistenings induce Mie scatter [7]. This may help to explain the reason why two IOLs were explanted with reports of surface glistening and glistening in the IOL optic as most probable cause [2] in spite of the fact that backward scatter appeared to be acceptable. The total light transmittance [28,29] of IOLs with glistenings and surface light scatter have been measured to be identical to that of clear control IOLs, implying that incident light is
forward scattered. The effects of retinal stray light should be measured in a forward direction and the scattered light distribution over the retina should be known in order to help understand and explain the origin of such visual complaints.

For cataract cases the forward scatter between 1 and 30 degrees is uniformly distributed over the retina [24], and the ratio between forward scatter and backward scatter in cataract has been shown to be on average a factor of approximately 2.3 [30], which is much less than that shown for glistenings due to the smaller size (0.7µm) of the responsible scatterers in cataract [31].

The results of this study show that increased retinal stray light causes decreased visual performance for all of the tests performed, even for stray light levels shown to be typical of those induced by glistenings in IOLs. The relevance of the chosen visual performance tests are supported by the chosen settings for the level of illuminance at the eye and the level of the stimulus luminance. Increased halo size has been reported to be correlated to forward light scatter [32]. Halo size measurement provides a psychophysical test of an otherwise highly subjective factor [33]. The luminance threshold test is a detection task intended to capture the impact of stray light in low light environments, where both glare source and stimuli are of a low strength. Degraded performance for this type of visual task may represent a risk factor under low light conditions such as night driving. The luminance threshold test was found to be the most sensitive visual performance test executed, and shows the dramatic effect stray light may have under these conditions. The measure illustrates for example that a 20 fold increase in luminance may be necessary under low light conditions in order to detect a pedestrian crossing the street in the presence of an oncoming car. The distance to respond to this hazard decreases by factor $\sqrt{20}$, indicating a potential reduction in the ability to react to targets while driving a car at night. In light of this fact, the complaints of some cataract patients who have adequate visual acuity may be better understood. In diagnosis of cataract, a luminance threshold test may help support an inconclusive slit exam of the crystalline lens. This may also be a diagnostic tool in cases where micro-vacuoles in intraocular lenses are suspected to be sources of the visual complaints. The outcomes of the luminance threshold test warrant further investigation into the development of a visual field perimetry protocol for this purpose by appropriately adapting size, angle and luminance of the stimulus, as well as the background luminance.

Finally, the contrast sensitivity test measures visual capability in an environment with higher luminance, where resolution tasks are required. Contrast sensitivity with and without glare are also relevant factors in driving [34]. Contrast sensitivity losses of 14% to 20%, as induced by low amounts of retinal stray light, have been predicted [7]. This demonstrates the clinical relevance of small elevated levels of retinal stray light. The retinal stray light effect on contrast sensitivity was largest with a glare source present at
2.5 degrees, causing a veiling luminance deteriorating the contrast of the image on the retina. The effect for a glare source located at 7 degrees is less due to the limited size of the halo radius. Individual variation in the relationship found between contrast sensitivity and stray light, as was measured in this study, is expected among the subjects, as age and neural factors also contribute to the contrast sensitivity function. Decreased CS has been reported in a number of intraocular lens studies with and without glistenings [15-19], and was of the same order of magnitude as measured in our study with the BPM¼ filter. The quick CSF method employed in this study allows for a more sensitive measurement of the contrast sensitivity than the 40% between consecutive levels used in standard contrast vision tests. This may explain why contrast loss has not always been concluded in intraocular lens studies on glistenings. CS loss with a higher magnitude was found for some types of cataracts [8,10-14]. In detail, these studies showed that the CS loss was largest for the cataract type posterior subcapsular opacity and less for nuclear and cortical opacities. These higher amounts of contrast losses measured in the past are of the same order of magnitude as measured in our study with BPM3 filter. Although our study induces stray light extra ocular, measuring visual effects with filters is a fair approximation to measurements with scatters in the eye.

In conclusion, retinal stray light correlates strongly with the outcomes of the methods used to measure visual function. Levels of retinal stray light as induced by glistenings and cataract have a measurable and significant impact on visual function.
References

Degradation of visual performance with increasing levels of retinal stray light
