Straylight in anterior segment disorders of the eye

van der Meulen, I. J. E.

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Chapter 11

IN-VITRO RECORDING OF FORWARD LIGHT-SCATTER BY HUMAN LENS CAPSULES AND DIFFERENT TYPES OF POSTERIOR CAPSULE OPACIFICATION

Maartje C.J. van Bree, MD1, Ivanka J.E. van der Meulen, MD2, Luuk Franssen, PhD2, Joris E. Coppens, PhD2, Bart L.M. Zijlmans, MD3, Thomas J.T.P. van den Berg, PhD4

1 Rotterdam Ophthalmic Institute, Rotterdam, The Netherlands;
2 Academic Medical Center, Department of Ophthalmology, Amsterdam, The Netherlands;
3 Netherlands Institute for Neuroscience, Royal Netherlands Academy, Amsterdam, The Netherlands; and
4 The Rotterdam Eye Hospital, Rotterdam, The Netherlands

ABSTRACT

Purpose
The purpose of the present study was to elucidate the effect of posterior capsule opacification (PCO) on the straylight domain of visual function. PCO is heterogeneous with regard to morphology and severity; both aspects contribute to its functional effect.

Methods
The isolated impact of capsule areas with specific morphology and severity on straylight was studied in-vitro by recording forward light-scatter. Forward light-scatter by four different capsule types, i.e., anterior capsule (AC), clear posterior capsule (PC), fibrotic and regeneratory PCO, was recorded at several visual angles with a goniometer, using different wavelengths. Angular ($\theta$) and wavelength dependencies ($\lambda^b$) were studied by determining exponents $a$ and $b$.

Results
Recorded straylight values of isolated capsule areas varied between $10\times$ below to $10\times$ above the value normal for the human eye, depending on the capsule’s condition (clear to opacified). The angular dependence of light scattered by clear PCs was weaker, whereas in the other capsule types it was stronger than in the normal eye. On average, the wavelength dependence of light scattered by different capsule types was similar, but the variation was considerable. At the smallest visual angles, increased angular and decreased wavelength dependence was found, especially in fibrotic and regeneratory PCO.

Conclusions
It was concluded that the range of straylight values found in-vitro in lens capsules properly corresponded to that found previously in in-vivo pseudophakics. Surprisingly, the wavelength dependence of PCO indicated that small-particle light-scattering is important in PCO. Refractile effects were more important at small visual angles, as indicated by the combined stronger angular and weaker wavelength dependence.
INTRODUCTION

Transparency of optical media, such as the crystalline lens and its surrounding lens capsule, is important for optimal visual function (VF). Cataract formation reduces the transparency of the crystalline lens. Cataract formation is largely age-related, and therefore affects visual function of a substantial part of the world population. Although a cataractous lens can be replaced by a transparent, artificial intra-ocular lens (IOL), the outcome of cataract surgery is frequently complicated by opacification of the lens capsule. Posterior capsule opacification (PCO) causes VF impairment similar to that caused by cataract. Therefore, PCO is a major hindrance to long-term VF restoration. The present study contributes to a better understanding of the impact of PCO on visual function.

PCO results from a wound-healing response caused by mechanical trauma during cataract surgery. Unfortunately, it is impossible to extract all lens cells. Wound-healing promotes residual lens epithelial cells (LECs) to proliferate, (trans)differentiate, and to deposit extracellular matrix, via autocrine and paracrine cell signaling. Migration of the cells into the space between IOL and posterior lens capsule causes opacification, and is called PCO. Clinically, two morphologically different PCO-types can be distinguished: PCO with a pearl appearance and PCO with a fibrotic appearance. Pearl-type PCO, or regeneratory PCO, is thought to be caused by proliferation and swelling of LECs. Fibrosis-type PCO is thought to be caused by LEC transdifferentiation.

As mentioned in the first paragraph of this section, PCO causes VF impairment: it deteriorates VF by reducing visual acuity and increasing intra-ocular straylight. The impact of PCO on visual acuity does not necessarily correspond to its impact on straylight. The distinct impact of PCO on visual acuity and straylight is expected to be related to the degree and localization of posterior capsule (PC) coverage by PCO. Moreover, which parameter of visual function is predominantly affected depends on the optical characteristics of PCO. Optical characteristics can be assumed to depend primarily on the characteristic size of PCO-irregularities: irregularities much larger than the wavelength of light refract light, and smaller sized particles scatter light. Refractile irregularities may predominantly affect the small-angle domain of visual function and reduce visual acuity, whereas scattering particles may predominantly affect the large-angle domain of visual function (visual angles beyond 1.0º) and increase straylight.

In the present study, forward light-scatter by PCO was recorded in-vitro with a goniometer set-up. The set-up records scatter intensities at the large-angle domain of visual function. The in-vitro setting allows studying light-scattering by a specific ocular structure, separately from light-scattering by other ocular structures. The concept for in-vitro forward light-scatter recordings with a goniometer set-up has been developed by Van den Berg et al. to study forward light-scatter...
by human crystalline lenses. Recently, the goniometer set-up was used to study light-scatter by PCO as it would appear functionally, i.e. light-scatter was recorded for a 4 mm circular central zone of the IOL-posterior capsule complex. PCO is heterogeneous and therefore most 4 mm central zones included clear PC areas and opacified PC areas of different type and severity. Central zone scatter characteristics result from composite scatter characteristics of all heterogeneous areas. As will be detailed in the Results section, scatter intensities can be translated into straylight values: the quantity defining the in-vivo visual function result. Straylight is expressed as the logarithm of the straylight parameter “s”, or log(s). For example, if the central zone is filled for 10% with PCO of log(s) = 2.0, and for 90% with PCO of log(s) = 1.0, the straylight value experienced by the patient is log(0.1*10^2 + 0.9*10^1) = 1.28.

For a better understanding of the light-scattering characteristics of heterogeneous PCO areas, in which the contributions of different PCO types and severities are mixed, the light-scattering characteristics of isolated areas with a specific PCO type and severity need to be investigated. In the present study, the goniometer set-up was used to study light-scatter by isolated, homogeneous capsule areas. The studied capsule areas were either clear or opacified, and opacified capsule areas had different severity and morphology.

METHODS

The techniques for specimen preparation and scattered light registration used in this study are largely identical to those previously described in detail. Therefore, the two following subsections only provide a summary.

Specimen preparation and selection
Pseudophakic donor bulbi were obtained from the Cornea Bank Amsterdam. Specimens were capsular bags (lens capsules) with an IOL. Initially, capsular bags were unfixated. After it had been concluded that a 1% paraformaldehyde fixative had no effect on the optical properties of capsular bags, bulbi were immersed in fixative (>24 hours) prior to preparation. Specimens were isolated using either of the two preparation techniques previously described. Isolated specimens were examined and selected by experienced ophthalmologists (I.J.E.M. and B.L.M.Z.), using a darkfield set-up with a darkfield ring light for retro illumination and slit illumination for reflected light examination. The purpose of darkfield examination was two-fold: (1) to ascertain close correspondence to in-vivo capsular bags, and (2) to identify small-sized IOL irregularities such as IOL glistenings or deposits. However, in none of the used specimens, IOL irregularities were observed. Whereas small-sized IOL irregularities and potential IOL-scatter might affect the large-angle domain, refractive IOL design only affects the small-angle domain. Therefore there were no inclusion criteria concerning IOL type or dioptic power.
Goniometer registration of scattered light

Light scattered by the specimens was recorded with a goniometer and a charge-coupled device camera. The specimen’s posterior part was oriented towards the camera. Light emitted by a halogen light source passed an infrared blocking filter and a narrowband interference filter with a peak wavelength of either 661 nm, 561 nm or 440 nm. The incident light passed the specimen in the same direction as in an in-vivo situation. The specimen scattered part of the incident light in different forward directions towards the camera, which served as the in-vitro counterpart of the in-vivo photoreceptors. The camera rotated in the horizontal plane around the specimen, and collected forward light-scatter at fixed angles corresponding to visual angles of $\theta = -22^\circ$, $-15^\circ$, $-11^\circ$, $-7^\circ$, $-5^\circ$, $-3^\circ$, $+3^\circ$, $+5^\circ$, $+7^\circ$, $+11^\circ$, $+15^\circ$ and $+22^\circ$. It should be noted that the visual angles apply to the specimen’s center. So, if the studied capsule area had a left-right decentration from the specimen’s center, the actual visual angles were slightly different from those specified above, and were not corrected. All visual angles were $>1^\circ$, and therefore represent the large-angle domain of the PSF.

For each specimen 13 goniometer registrations per wavelength were obtained: 12 grayscale images corresponding to the 12 visual angles, and one grayscale image collected at the $\theta = 0^\circ$ position. Images collected at the $\theta = 0^\circ$ position can be compared with clinical retrograde slitlamp images, although the light direction is reversed. At the $\theta = 0^\circ$ position, non-scattered, directly transmitted light is recorded. In the presence of opacified areas some of the incident light will be scattered. Consequently, the amount of recorded transmitted light is reduced and opacified areas appear as less intense, shadowy patterns (Figure 11.1A).

FIGURE 11.1 Image of a representative regeneratory PCO specimen captured at the $\theta = 0^\circ$ position, using the goniometer set-up. Selected lens capsule areas are indicated: an anterior capsule (AC) area, two posterior capsule opacification (PCO) areas of different severity, and a clear posterior capsule (PC) area (A). Their scatter characteristics were recorded using a blue light filter (440 nm, blue curves), a green-yellow light filter (561 nm, green curves) and a red light filter (660 nm, red curves) (B).
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Straylight parameter
The goniometer set-up was calibrated according to the PSF-definition of the Commission Internationale de l’Eclairage (CIE) (see http://www.cie.co.at/). The CIE norm of the PSF of a healthy, young eye was used as a reference. Scatter intensities are expressed as absolute PSF-values in terms of the straylight parameter “s”, according to
\[ s = \theta^2 \times \text{PSF}(\theta). \]
The logarithm of s, or \( \log(s) \), was used. By using \( \log(s) \) as a unit, the in-vitro values recorded in the present study can directly be compared to in-vivo values measured using the C-Quant instrument (Oculus GmbH, Wetzlar, Germany). Theoretical details concerning the comparison of in-vivo and in-vitro \( \log(s) \) values are given elsewhere.

Selection of isolated capsule areas
To represent the heterogeneous nature of human capsular bags, isolated capsule areas with different morphology and severity were selected. Selected capsule areas were divided into 4 categories; (A) anterior capsule (AC) areas, (B) relatively clear PC areas, (C) areas of fibrotic PCO, and (D) areas of regenerative PCO. Because AC and PC areas overlap, light scattered by AC areas could not be isolated from light scattered by PC areas. Therefore, only AC areas overlapping relatively clear PC areas were eligible. Both clear and fibrotic AC areas were selected. Using Matlab software (MathWorks, Inc., Natick, Massachusetts; version 7.11.0.584), selected capsule areas were specified as regions of interest. Examples of selected capsule areas are shown in Figure 11.1A. As explained earlier in the Methods section, for each region of interest \( \log(s) \) values were recorded at all visual angles and wavelengths (Figure 11.1B).

Optical characteristics
The nature of the angular and wavelength dependence can be used to assess the particle-size dominating light-scattering in different parts of the lens capsule. Particles much smaller than the wavelength of light typically show a weak angular and a strong wavelength dependence, whereas particles larger than the wavelength of light typically show a strong angular and a weak wavelength dependence.

The angular dependence of intraocular straylight can be described as \( \theta^a \), with approximate exponent \( a = -2 \) (Figure 11.2, dashed curves). It was found that \( a = -2 \) in young, healthy eyes and in aging, cataractous eyes. In this study, the angular dependence of light scattered by the different lens capsule types was assessed by determining exponent \( a \).

The wavelength dependence of scattered light can be described as \( \lambda^b \). Light scattered by very small particles is called Rayleigh scatter, and has a strong wavelength dependence with exponent \( b = -4 \). Light scattered by particles much larger than the wavelength of light typically has no wavelength dependence, with exponent \( b = 0 \). The wavelength dependence of light scattered
Forward light-scatter by isolated PCO areas

by particles of intermediate size can be described as $\lambda^b$, with $-4 < b < 0$. In the present study, the wavelength dependence of light scattered by different lens capsule types was assessed by determining exponent $b$.

Detailed knowledge of optical characteristics such as angular and wavelength dependence, can be obtained by calculating exponents $a$ and $b$. The exponents are important if one aims to derive effective particle size with physical-optical theory. However, in the present study, exponents $a$ and $b$ were used to elucidate the impact of different capsule types on the straylight part of visual function.

RESULTS

As previously described, 25 representative PCO specimens were identified by experienced ophthalmologists. Eleven AC areas, 10 clear PC areas, 7 areas of fibrotic PCO and 13 areas of regeneratory PCO were selected in the present study. Examples of isolated capsule areas are shown in Figure 11.1. The remainder of this Results section describes findings for the four
different capsule types, concerning (1) scatter intensity (first subsection and Figure 11.2), (2) angular dependence (second subsection and Figures 11.3-11.4), and (3) wavelength dependence (third subsection and Figures 11.5-11.6).

Intensity of light-scatter by different capsule types

The variation in scatter intensity found in different capsule types is illustrated by Figure 11.2. It shows the 581 nm scatter characteristics of all selected (A) AC areas, (B) clear PC areas, (C) areas of fibrotic PCO, and (D) areas of regeneratory PCO. The log(s) parameter is shown as a function of visual angle. The thin, solid curves represent individual isolated capsule areas, and the thick, solid curves are average curves for each of the four different capsule types. The thick dashed curve represents the PSF for a healthy and young eye (expressed in terms of the straylight parameter), and can be used as a reference. As mentioned in the Methods section, there is a close correspondence of in-vivo and in-vitro log(s) values, both theoretically and practically.\(^6\) The clinical C-Quant instrument measures straylight at approximately \(\theta \approx 7^\circ\). Therefore, we will focus on averaged log(s) values obtained at \(-7^\circ\) and \(+7^\circ\): those values can be directly compared to in-vivo straylight values obtained in the clinic. The scatter intensity found in AC at \(-7^\circ\) and \(+7^\circ\) ranges from log(s)= 0.0 to log(s)= 2.1, with an average of log(s)= 1.2 (Figure 11.2A). The scatter intensity found in clear PC areas is relatively low and ranges from log(s)= 0.1 to log(s)= 1.1, with an average of log(s)= 0.6 (Figure 11.2B). The scatter intensity in fibrotic PCO areas ranges from log(s)= 0.7 to log(s)= 1.4, with average log(s)= 1.2 (Figure 11.2C). The scatter intensity in the regeneratory PCO areas ranges from log(s)= 0.6 to log(s)= 2.0, with an average log(s)= 1.2 (Figure 11.2D).

Figure 11.2 shows that in most areas, similar scatter intensities were recorded at positive and negative visual angles. However, in some capsule areas slightly asymmetrical scatter intensities were recorded. These were observed if the selected capsule area was left-right decentrated in relation to the specimen’s center. As described in the Methods section, such decentration causes a small error in actual visual angle, resulting in slightly asymmetrical scatter intensities. Finally, in fibrotic PCO areas of similar severity, different scatter intensities were recorded; the scatter intensity is much stronger in some areas as compared to other areas (Figure 11.2C). As will be detailed in the following subsection, differences in angular dependence were also found in these areas.

Angular dependence of light-scatter by different capsule types

The shapes of curves obtained from distinct capsule areas were compared; most curves of PCO areas (Figures 11.2C and 11.2D) are steeper than those of AC (Figure 11.2A) and clear PC areas (Figure 11.2B). In other words, the angular dependence of light scattered by PCO areas is on average stronger than that scattered by AC and clear PC areas. The shape of the average curves was
Forward light-scatter by isolated PCO areas

also compared with that of the reference curve. The shape of the AC and fibrotic PCO curves was similar to that of the reference curve. In other words, the angular dependence of light scattered by AC and fibrotic PCO areas is similar to the average angular dependence of approximately $\theta^{-2.2}$ found in healthy, young eyes (Figures 11.2A and 11.2C). The angular dependence of clear PC areas is weaker than in a healthy, young eye (Figure 11.2B), whereas in regeneratory PCO it is stronger than in a healthy, young eye (Figure 11.2D).

By calculating the slope, or exponent $a$, of the log($s$) curves shown in Figure 11.2, shape differences between log($s$) curves and shape differences between the log($s$) curves and the reference curve for a healthy, young eye can be assessed in detail. The slope ($a$) of each line segment connecting successive visual angles (Figure 11.2; thin, solid curves) was calculated and plotted as a function of visual angle for all (A) AC areas, (B) clear PC areas, (C) fibrotic PCO areas and (D) regeneratory PCO areas (Figure 11.3; thin, solid curves). The average exponent $a$ for each of the four different capsule types is shown by thick, solid curves. The reference exponent for a healthy, young eye is shown by thick, dashed curves, and can be used as a reference. Remember from the ‘Optical characteristics’ subsection of the Methods, that the reference exponent is approximately -2. Its precise value depends on visual angle: it varies over the angular range from -1.9 to -2.4, and approaches -2.2 at 7°. Figures 11.3A and 11.3C show that the average exponent $a$ of the AC and fibrotic PCO areas is slightly stronger than the reference exponent, especially at the largest angles of the angular range; it is on average -2.3 for both the AC and the fibrotic PCO areas. Figure 11.3B shows that the average exponent $a$ of clear PC areas is slightly weaker than the reference exponent at visual angles $22^\circ > \theta > -15^\circ$ and $22^\circ < \theta < 15^\circ$, whereas it is stronger at the other visual angles; the average exponent $a$ is -1.9. Figure 11.3D shows that the average exponent $a= -2.7$ for the regeneratory PCO areas is stronger than the reference exponent at all visual angles, especially at the largest angles of the angular range.

As mentioned in the first subsection of the Results, light scattered by fibrotic PCO areas could vary in intensity. In addition, the angular dependence of light scattered by these areas could vary. This is illustrated by the fibrotic specimen in Figure 11.4A. In Figure 11.4A, PCO areas are represented by shadowy patterns. The intensity of the shadowy patterns of PCO areas 1 and 2 is similar (Figure 11.4A), which suggests similar PCO severity. However, their scatter intensity and angular dependence is different: the curves of PCO area 2 are rather flat, whereas those of PCO area 1 have steeper slopes (Figure 11.4B). PCO areas 1 and 2 have fiber structures of different orientations. As described in a previous study, fiber structures with a convex surface, such as those shown in Figure 11.4A, are expected to behave optically as rod structures. The optical behaviour of structures with a rod-like shape is called the “Maddox-rod phenomenon” and refers to the phenomenon that in rod structures incident light is deflected as a line perpendicular to the
The angular dependence of scattered light is described by \( \theta_a \). The thin, solid curves show exponent \( a \) as a function of visual angle for each anterior capsule area \((n = 11)\) (A), each clear posterior capsule area \((n = 10)\) (B), each fibrotic PCO area \((n = 7)\) (C) and each regeneratory PCO area \((n = 13)\) (D) \((\lambda = 561 \text{ nm})\). The thick, solid curves represent the average exponent \( a \) for the four different capsule types. The thick, dashed curves represent the strength of the angular dependence in a healthy, young eye.

![Figure 11.3](image)

FIGURE 11.3 The angular dependence of scattered light is described by \( \theta_a \). The thin, solid curves show exponent \( a \) as a function of visual angle for each anterior capsule area \((n = 11)\) (A), each clear posterior capsule area \((n = 10)\) (B), each fibrotic PCO area \((n = 7)\) (C) and each regeneratory PCO area \((n = 13)\) (D) \((\lambda = 561 \text{ nm})\). The thick, solid curves represent the average exponent \( a \) for the four different capsule types. The thick, dashed curves represent the strength of the angular dependence in a healthy, young eye.

rod’s axis. So, horizontally oriented fibers deflect incident light as a vertical line, and vertically oriented fibers deflect it as a horizontal line. The optical set-up used in this study records light spreading in the horizontal plane. So, in the presence of vertically oriented fibers strong light spreading is recorded, whereas in the presence of horizontally oriented fibers weaker light spreading is recorded. In PCO area 2 the fiber structures are oriented horizontally, whereas in area 1 they are oriented vertically (Figure 11.4A); this translates to weaker scatter intensities recorded in area 2 than in area 1 (Figure 11.4B). Furthermore, the angular dependence of light spreading by area 2 is weaker than that by area 1 (Figure 11.4B). For comparison, two regeneratory PCO areas of similar severity, PCO areas 3 and 4, are shown in Figure 11.4C. None of the areas has a fiber structure, and a similar scatter intensity and angular dependence is found in both areas (Figure 11.4D). The curves of PCO areas 1-4 have two characteristics in common at the smallest angles in the angular range, (1) an increasing slope, indicating increasing angular dependence, and (2) a narrowing in the spacing of the blue, green and red curves, indicating decreasing wavelength dependence (Figures 11.4B and 11.4D).
Wavelength dependence of light-scatter by different capsule types

Figures 11.5 and 11.6 focus on wavelength dependencies. The solid blue, green and red curves in Figure 11.5 show average scatter characteristics of all selected (A) AC areas, (B) clear PC areas, (C) areas of fibrotic PCO, and (D) areas of regeneratory PCO, recorded with 440 nm, 561 nm and 661 nm. Again, the black, dashed curves represent a healthy, young eye, to be used as a reference. Figure 11.5 shows that for each capsule type, the corresponding blue, green and red curves have a similar shape. To put it differently, for the three wavelengths the angular dependence is similar. Furthermore, Figure 11.5 shows that for all capsule types, the lowest log(s) values were recorded at 661 nm and the highest at 440 nm, i.e. scatter intensity increases with decreasing wavelength. The strength of the wavelength dependence is indicated by the spacing of the blue, green and red curves. In case scattered light has no wavelength dependence, the blue, green and red curves...
would show no spacing, whereas in case of strong wavelength dependence the curves would be widely spaced. Figure 11.5 shows a similar spacing of the solid blue, green and red curves for the different capsule types. However, especially in the fibrotic PCO and regeneratory PCO areas, the spacing between the blue, green and red curves decreases at the smallest angles of the angular range.

Differences in wavelength dependence can be assessed in detail by determining exponent $b$. As mentioned in the previous paragraph, at a particular visual angle different scatter intensities were recorded at 661, 561 and 440 nm, with the lowest log values at 661 nm and the highest log values at 440 nm (Figure 11.5). For each angle, exponent $b$ was derived from the scatter intensities recorded at 661, 561 and 440 nm. In Figure 11.6, exponent $b$ is plotted as a function of visual angle for all (A) AC areas, (B) clear PC areas, (C) fibrotic PCO areas and (D) regeneratory PCO areas (thin, solid curves). The average exponent $b$ (see the 'Optical characteristics' subsection of the Methods) for each of the four different capsule types is shown by thick, solid curves. The average exponent $b$ is around -1.5, but there is quite some variation, possibly caused by the fact that derivatives (slopes) are sensitive to noise in the recordings. The narrowing in the spacing between the blue, green and red curves at the smallest angles of the angular range in AC, fibrotic

FIGURE 11.5 Average scatter characteristics of anterior capsule areas (n = 11) (A), clear posterior capsule areas (n = 10) (B), fibrotic PCO areas (n = 7) (C) and regeneratory PCO areas (n = 13) (D), obtained with a blue light filter (440 nm, blue curves), a green-yellow light filter (561 nm, green curves) and a red light filter (660 nm, red curves). The dashed, black curves are reference curves for a healthy, young eye.
PCO and regeneratory PCO areas that was mentioned in the second subsection of the Results, indicates a decrease in wavelength dependence, which is confirmed by Figures 11.5A, 11.5C and 11.5D. On average, the value of exponent $b$ is less negative at the smallest angles as compared with its value at larger angles, which illustrates the decreasing wavelength dependence more clearly (Figures 11.6A, 11.6C and 11.6D).

**DISCUSSION**

In the present study we determined light-scattering by isolated capsule areas. Light-scattering is expressed in terms of PSF. Because the straylight parameter (log($s$)) was used as a unit, the present in-vitro findings and in-vivo findings previously obtained with the C-Quant instrument can be compared in absolute sense. This will be elaborated in the following subsection.

In-vivo population studies in healthy, young eyes found a reference value of log($s$) = 0.9. In pseudophakics with clear and opacified posterior capsules, found log($s$) values ranging from log($s$) = 0.6 to 2.0 with an average of 1.3. In pseudophakics with PCO

![Figure 11.6](image-url)
and an indication for neodymium:YAG laser capsulotomy, log(s) values ranging from log(s)= 1.1 to 2.4, with an average of 1.6 were found. The in-vivo upper limits in pseudophakics of log(s)= 2.0 and 2.4 approximately correspond to the highest value of log(s)= 2.0 found in a PCO area in the present in-vitro study. The log(s) value of 2.0 found in an isolated area of severe PCO corresponds to a 12.6-fold increase (corresponding to 1.1 log units) in straylight, as compared to the reference value of 0.9 in healthy, young eyes. In-vitro, a lower limit of log(s)= 0.1 was found in clear capsules, which does not correspond to the in-vivo lower limit of log(s)= 0.6 found in a population of pseudophakics including clear capsules. The underlying reason is that in-vitro log(s) values represent only the amount of straylight caused by the lens capsule-IOL complex, whereas in-vitro log(s) values represent the amount of straylight in the pseudophakic eye as a whole, including the contribution of other ocular structures to intraocular straylight, e.g., light-scatter by the cornea and vitreous, pigmentation-dependent light transmission by the iris and sclera, and pigmentation-dependent light reflection by the fundus. It has been estimated that 2/3 of the total amount of straylight in a healthy and young eye, i.e. corresponding to log(s)= 0.7, is caused by all these ocular structures together, the crystalline lens excepted.

As described in the Introduction, the straylight value experienced by the patient results from the combined contribution of clear and opacified capsule areas of different severity. In the previous in-vitro study, log(s) values were recorded over a 4 mm circular central zone. The 4 mm log(s) values found in the previous in-vitro study ranged from log(s)= 0.1 to 1.6 with an average of 1.0. Comparing the already mentioned in-vivo upper limits of log(s)= 2.0 and 2.4 in pseudophakics to the upper limit of log(s)= 1.6 found in the previous in-vitro study, it appears that the latter is much lower. However, one should realize that the value of 2.4 concerned pseudophakic patients with PCO and an indication for neodymium:YAG capsulotomy, whereas the in-vitro study concerned random pseudophakic eyes.

It should be noted that in the present study a wide range of scatter intensities was observed in areas that were marked as clear PC. As described in the Methods section, capsules were examined by experienced ophthalmologists, using a darkfield microscopy set-up that included slitlamp examination with reflected light and retro illumination. Despite the careful examination, some PC areas that were marked as clear might have had minimal, sub-clinical opacification. As described in the Methods section, it can also not be ruled out that in some truly clear PC areas, diffuse scatter processes induced by IOLs might have caused a small amount of scatter. Because of these two issues, (1) possible sub-clinical opacification and (2) potential scatter by IOLs, the precise level of scatter-intensities obtained in areas marked as clear PC may not faithfully represent the clear capsule.
The four different capsule types selected in the present study showed distinct scatter characteristics, especially concerning angular dependence. The distinct angular dependence of the capsule types was characterised by log(s) curves with a distinct shape (Figure 11.2), and therefore a different exponent \(a\) (different slope) (Figure 11.3). The angular dependence of clear PC areas was weaker than in a healthy, normal eye, whereas in AC, fibrotic PCO and regeneratory PCO areas it was stronger than in a healthy, young eye (Figure 11.3). Apart from different capsule types, areas of different severity were included. The results indicate that severity differences are characterised by differences in scatter intensity, resulting in vertical displacement of log(s) curves (Figure 11.2). In summary, differences in angular dependence result in log(s) curves with a distinct shape, and differences in scatter intensity result in vertical displacement of the curves (Figure 11.2).

Besides determining the scatter intensity and angular dependence of light scattered by isolated capsule areas, the present study also assessed wavelength dependence. Detailed assessment of wavelength dependence showed that exponent \(b\) was approximately \(-1.5\) in all capsule types, but with considerable variation. Especially in the fibrotic PCO and regeneratory PCO areas, exponent \(b\) was less negative at the smallest angles, which indicates that the wavelength dependence decreases with decreasing angle. As described in the second subsection of the Results, a combined increased angular dependence and decreased wavelength dependence at the smallest angles of the angular range, was found in especially fibrotic (Figures 11.5C and 11.6C) and regeneratory PCO areas (Figures 11.5D and 11.6D). According to optical light-scattering theory,\textsuperscript{15,16} the combination of these optical characteristics implies the presence of light spreading caused by refractile PCO-structures. As mentioned in the Introduction, light refraction is caused by structures much larger than the wavelength of light. Rod-like fibers present in fibrotic PCO and pearl-like structures present in regeneratory PCO, could be such refractile structures. An example of light-spreading by refractile PCO structures is the Maddox-rod phenomenon described in the second subsection of the Results.

We expected the light-scattering characteristics of PCO to be drastically different from those of the crystalline lens, due to differences in morphological appearance. In the large-angle domain, light-scattering in the crystalline lens is dominated by particles of about 1 micrometer in size.\textsuperscript{15,16} However, cells that constitute PCO are much larger. So, the angular and wavelength dependencies found in the present study surprised us. Especially the wavelength dependence found in PCO clearly indicates that, based on physical-optical light-scattering theory,\textsuperscript{15,16} small particle light-scattering is also important in PCO. However, apart from small particle scattering, the current data also indicate that refractile effects become more important at smaller visual angles, as witnessed by the combination of stronger angular and weaker wavelength dependence.
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REFERENCES