Comparison of ocular straylight after implantation of various multifocal intraocular lenses

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ABSTRACT

A comprehensive review of the effect of multifocal intraocular lens (IOL) designs on post-operative ocular straylight was performed. Studies reporting straylight values obtained with the natural pupil using the C-Quant device after uneventful multifocal IOL implantation were included. The IOLs were categorized based on their material characteristics; that is, hydrophobicity and presence of colored chromophores. Age adjustment was achieved using the straylight age-dependency norm for pseudophakic eyes. This norm also served as a reference for comparing mean straylight levels of the various IOLs. The literature review identified 10 studies reporting 9 multifocal IOL designs. The hydrophilic IOLs showed less straylight than the hydrophobic IOLs by 0.08 log(s) (P = .001). Blue violet light–filtering IOLs showed less straylight than standard IOLs by 0.04 log(s), which was not statistically significant (P = .32). Hydrophobicity was a factor that significantly affected straylight in multifocal IOLs.

INTRODUCTION

Since the introduction of the first intraocular lens (IOL) in 1949,[1] tremendous advances in IOL technology have been made. Modern IOLs are not limited to correcting only post-operative aphakia. They can also reduce ocular aberrations, protect the retina against ultraviolet and blue light, and provide useful near and intermediate vision in addition to standard distance vision. Many IOLs that vary in optical design and material are available to healthcare professionals. This may influence not only the postoperative prediction error and visual acuity, but also other aspects of quality of vision such as the visual effects of light scattering; *i.e.*, straylight and disability glare.

Disability glare originates from light scattered in the eye due to imperfections in the optical media.[2] The scattered light causes a veil of light over the retina that degrades contrast of the retinal image. The visual effect of light scattered around a bright light source is called straylight.[3] Disability glare has been defined as identical to straylight by the Commission Internationale de l'Eclairage[4] and can be expressed by its (equivalent) luminance as the ratio of light scattered toward the retina at a certain angular distance and the total amount of light entering the eye. This is the basis on which straylight is measured by the C-Quant straylight meter (Oculus), an instrument that is commercially available for use in clinical practice.[5] The amount of straylight is expressed logarithmically as log(s). The effect on visual performance of an increase of 0.1 log(s) is comparable to that of losing 1 line of visual acuity on the logMAR scale.[6] Straylight elevation has been associated with several clinical conditions, particularly cataract, and with several corneal dystrophies, corneal haze, and vitreous turbidity[7] It causes numerous visual difficulties such as blinding by headlights of oncoming cars, halos around light sources, irritability to sunlight, and loss of color vision.[3,7]

Several authors have studied the effect of IOLs on postoperative straylight. Five studies compared monofocal and multifocal IOLs.[8–12] Two found a significantly lower straylight value in the monofocal population,[9,11] but the other 3 reported insignificant differences between the monofocal and multifocal IOLs.[8,10,12] The reason for this discrepancy is not understood. However, differences in multifocal designs and to what extent they affect the postoperative straylight have been investigated. Ehmer et al.[13] found that diffractive multifocal IOLs scatter more light than their refractive counterparts. In other studies,[14–16] straylight did not differ significantly between various diffractive multifocal IOLs. However, it is possible that not only optical design but also material properties such as hydrophobicity or the presence of colored chromophores influence the amount of straylight.

Because patients' expectations have increased over time, one challenge for multifocal IOLs is to optimize factors other than visual acuity, such as straylight, that affect visual quality. To address this issue, we looked at the potential effect on straylight of design and material differences between multifocal IOLs by meta-analysis of data from published studies.

METHODS

A comprehensive literature review of PubMed, ProQuest, Embase, Medline, and Google Scholar was performed to identify studies of straylight in pseudophakic eyes. The criteria of the selection process and data acquisition were as follows: Articles on multifocal IOLs were included if they fulfilled the following conditions: enrollment of healthy subjects with no ocular comorbidities or history of eye surgeries except cataract surgery or refractive lens exchange; absence of intraoperative and postoperative complications, for example, posterior capsule opacification; straylight measurements performed with the natural pupil using the C-Quant straylight meter; and disclosure of the implanted multifocal IOLs. Ten of the 230 records identified were included and analyzed (**Figure 1**).

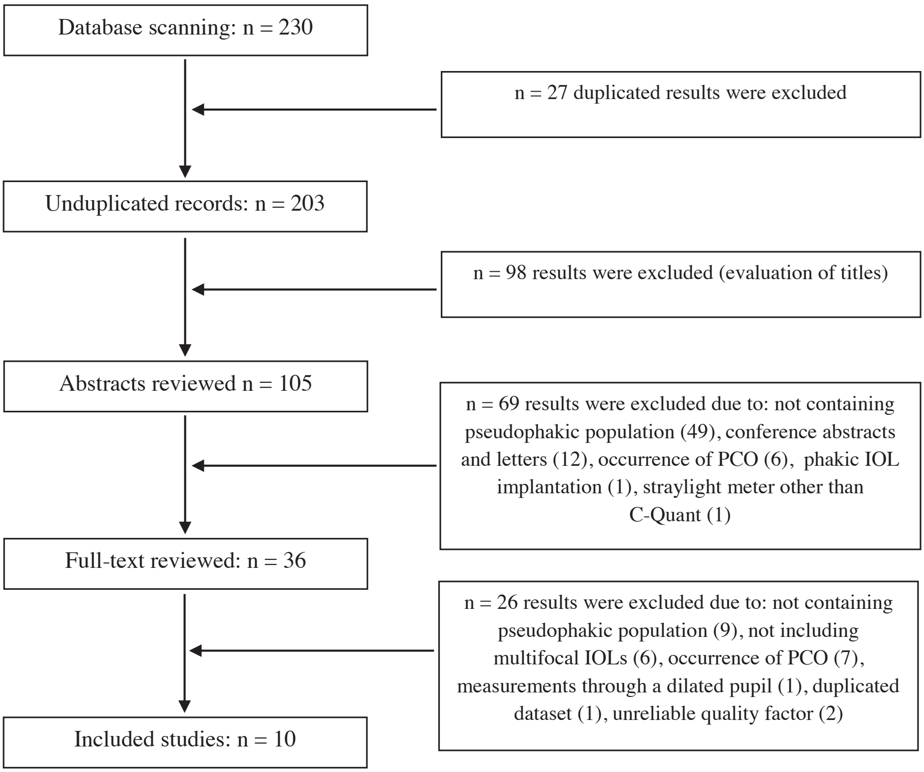

Figure 1. Illustration of the systematic literature review (IOL = intraocular lens; PCO = posterior capsule opacification).

Intraocular Lenses

Results of 9 IOL models from 5 manufacturers were available in the 10 eligible articles,[8–17] leading to 18 unique results. The IOL models along with their general features and the reported straylight values are presented in **Table 1**.

The IOLs use 4 technologies to achieve their multifocality. The Tecnis ZM900 (Abbott Medical Optics, Inc.) and the AT LISA 809M (Carl Zeiss Meditec AG) are full-optic multifocal diffractive IOLs; *i.e.*, the height of the diffractive steps remains constant, allowing a light distribution that is independent of pupil size.[18] The apodized diffractive pattern used in the Restor SA60D3, SN60D3, SN6AD3, and SN6AD1 (all from Alcon Laboratories, Inc.) and the Seelens MF (Hanita Lenses RCA Ltd.) is distinct from the full-diffractive IOL by a gradual decrease in the height of the diffractive steps from the center of the IOL, yielding a dominance of the far focus when the pupil size increases.[18] A drawback of using the diffractive technology is the energy spread up to 18% to higher-order foci.[18] This effect does not occur with the refractive multifocal IOLs. The Mplus LS-313 (Oculentis GmbH) is a rotationally asymmetric refractive multifocal IOL that contains a segment embedded for near vision. The Rezoom (Abbott Medical Optics, Inc.) is a rotationally symmetric refractive multifocal IOL.

The collected data were additionally categorized according to general properties such as the presence or absence of colored chromophores in the IOL material and the water content. Hydrophilic IOLs covered by a hydrophobic surface such as the AT LISA 809M and Mplus LS-313 were allocated to the hydrophilic group along with the Seelens MF, as these IOLs correspondingly contain 25% of water and are generally considered hydrophilic. In the study by De Vries et al.,[15] spherical (Restor SN60D3) and aspheric (Restor SN6AD3) diffractive multifocal IOLs were analyzed as a single set of data because it was shown that straylight did not differ significantly between these IOLs (**Table 1**).

Statistical Analysis

Because straylight has been found to be age dependent in pseudophakic eyes,[19–21] age adjustment of straylight values was performed to enable the evaluation of differences in light scattering between IOLs implanted in eyes of various age groups. The correction was achieved using the pseudophakic norm published in a review article.[19] To compare an average result of a single IOL model with that in the other included studies, the mean age of each population was used to calculate the straylight norm value based on the overall straylight norm formula in the pseudophakic eye as follows:

$$\text{Straylight} = 0.0044 \times \text{Age} + 0.89 \quad [\log(s)]$$

The difference between the mean straylight and the normative value, which is called the normalized difference, was then assessed. This resulted in a negative value or positive value depending on whether the postoperative value was below (less straylight) or above (more straylight) the pseudophakic reference, respectively (*i.e.*, negative values refer to less straylight). The cross-center comparison of straylight and its standard deviation (SD) involved the calculation of the arithmetic and weighted mean.

The significance of differences between the means of the IOL models was evaluated by the Kruskal-Wallis analysis of variance (ANOVA) test. The general properties of materials for IOLs listed in **Table 1** were compared with the Mann-Whitney U test. The nonparametric approach was chosen because of the possible inhomogeneous variance of the studied populations. For these tests, raw data were required. For 2[8,17] of the 10 articles, the raw data were supplied by the original authors; for 4 articles,[9,10,12,13] the raw data were supplied by digitization of the original plots using GSYS2.4 software.[A]

For the 4 remaining papers,[11,14–16] raw data could not be obtained and thus were not used for this part of the analysis; however, these papers were used for comparison of the mean straylight and its SD. Age adjustment of the results was done for each individual eye using the pseudophakic norm (**equation 1**). Subsequently, the residuals of the following

Table 1. Characteristics of the IOL models and clinical outcomes in the included studies.

IOL Model	Manufacturer	IOL Type	Material	
SeeLens MF	Hanita Lenses RCA Ltd	Diffractive apodized	Hydrophilic	Acrylic
AT LISA 809M	Carl Zeiss Meditec	Full diffractive	Hydrophilic (hydrophobic surface)	Acrylic
Mplus LS-313	Oculentis GmbH	Refractive (segment)	Hydrophilic (hydrophobic surface)	Acrylic
ReSTOR SA60D3	Alcon Laboratories	Diffractive apodized	Hydrophobic	Acrylic
ReSTOR SN60D3 Restor SN6AD3	Alcon Laboratories	Diffractive apodized	Hydrophobic	Acrylic
ReSTOR SN6AD1	Alcon Laboratories	Diffractive apodized	Hydrophobic	Acrylic
Tecnis ZM900	Advanced Medical Optics	Full diffractive	Hydrophobic	Silicone
ReZoom	Advanced Medical Optics	Refractive (zonal)	Hydrophobic	Acrylic
Total				

FU = follow-up; IOL = intraocular lens; NA = not available; VBL = violet blue light
*Intraocular lens names are listed as spelled by the manufacturer and not per journal style
†First author

groups were compared: hydrophilic versus hydrophobic and blue violet light–filtering IOLs versus standard IOLs. The significance level was a P value less than 0.05. The effect size was measured using the Cohen d parameter with the 95% confidence interval (CI). The analysis was performed using the statistical package Statistica 10 (Statsoft, Inc., 2011).

LITERATURE REVIEW

The mean straylight value of the 9 IOL models that were included in the 10 studies[8–17] (822 eyes) was 1.18 log(s) ±0.19 (SD), and the mean patient age was 66 ±9 years (**Table 1**). The individual postoperative straylight results in the study populations are presented in **Figure 2**.

Violet/ blue-light filter	Eyes (n)	Mean log(s) ±SD	Mean age (Y) ±SD [Range]	No. of eyes per study	Follow-up (Mo)	First author (year)
Yes	38	1.05±0.14	57 ±9 [46, 84]	38	3	Lapid-Gortzak (2014)[17]
No	109	1.13±0.18	55 ±7 [46, 67]	25	3	Lapid-Gortzak (2014)[17]
			67 ±9 [NA]	84	4 - 8	Maurino (2015)[16]
No	42	1.13±0.18	60 ±6 [51, 72]	32	3	Lapid-Gortzak (2014)[17]
			65 ±7 [52, 76]	10	> 3	Ehmer (2011)[13]
No	119	1.19±0.18	72 ±8 [55, 83]	37	18	Hofmann (2009)[10]
			75 ±10 [35, 88]	60	6	De Vries (2008)[9]
			64 ±11 [45, 83]	22	6	Cerviño (2008)[8]
Yes	92	1.16±0.16	68 ±11 [NA]	45	6	De Vries (2010)[15]
		1.19±0.19	65 ±10 [NA]	47		
Yes	304	1.21±0.18	62 ±7 [45, 72]	52	3	Lapid-Gortzak (2014)[17]
			64 ±9 [NA]	68	6	De Vries (2010)[14]
			66 ±8 [NA]	100	6	Peng (2012)[11]
			68 ±10 [NA]	84	4 - 8	Maurino (2015)[16]
No	95	1.21±0.26	59 ±10 [43, 70]	10	> 3	Ehmer (2011)[13]
			67 ±11 [32, 90]	85	4	Wilkins (2013)[12]
No	23	1.19±0.22	69 ±11 [56, 85]	13	6	Cerviño (2008)[8]
			60 ±14 [26. 78]	10	> 3	Ehmer (2011)[13]
	822	1.18±0.19	66 ±9 [26, 90]			

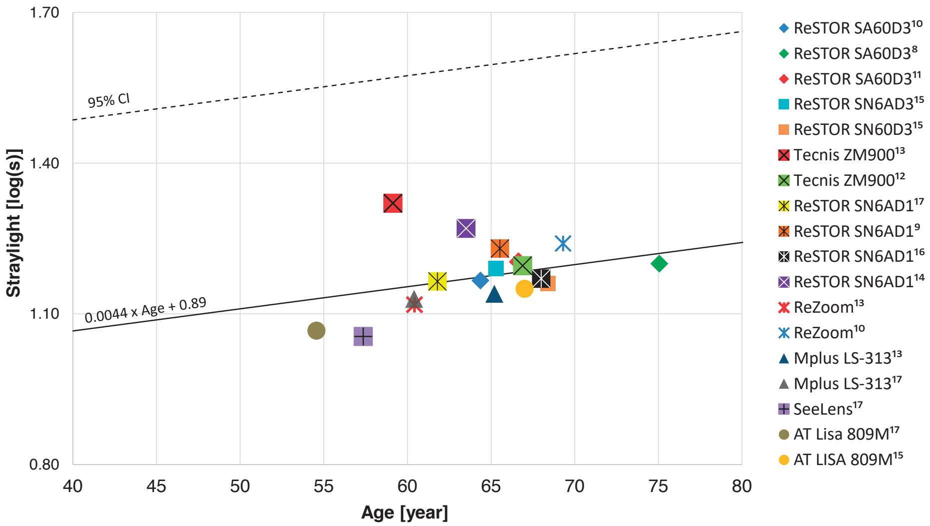

Figure 2. Mean straylight of the individual studies and IOLs as a function of age. The solid line represents the straylight pseudophakic norm and the dashed line, the 95% CI.

Figure 3 shows the SD level for the studied IOLs. This evaluation showed, on average, a slightly lower SD in the multifocal group (±0.19 log[s]) than in the overall normal pseudophakic population (±0.21 log[s]) as described in a recent review.[19]

After age correction, the mean straylight value remained at the same level of 1.18 log(s). The mean differences between the postoperative straylight values and the norm of the Seelens MF, AT LISA809M, Mplus LS-313, Restor SN6AD3 and SN60D3, Restor SA60D3, Rezoom, Tecnis ZM900, and Restor SN6AD1 IOLs were -0.088 log(s), -0.041 log(s), -0.029 log(s), -0.009 log(s), -0.005 log(s), 0.009 log(s), 0.028 log(s), and 0.035 log(s), respectively (**Figure 4**).

A total of 394 raw records were available. The differences between the IOL models proved to be statistically significant (P = .01). The statistical analysis of the material characteristics with the Mann-Whitney U test showed that the hydrophobic material was associated with significantly more straylight than the hydrophilic material by 0.08 log(s) (P = .001; d = 0.39; CI, 0.16-0.61). The 9 IOLs were therefore categorized into hydrophobic (289 eyes) and hydrophilic (105 eyes) groups, and the Kruskal-Wallis ANOVA tests of the IOL models were repeated for each group. The differences within the hydrophobic group (P = .22) and the hydrophilic group (P = .39) were insignificant. No effect of colored chromophores in IOL materials on ocular straylight was found. Although the blue violet light–filtering IOLs induced, on average, 0.04 log(s) less straylight than the standard IOLs, the difference was not statistically significant (P = 0.32; d = 0.16; CI, -0.07 to 0.40). The comparison between the hydrophobic and hydrophilic materials as well as between blue violet light–filtering and standard IOLs are presented in **Figure 5**.

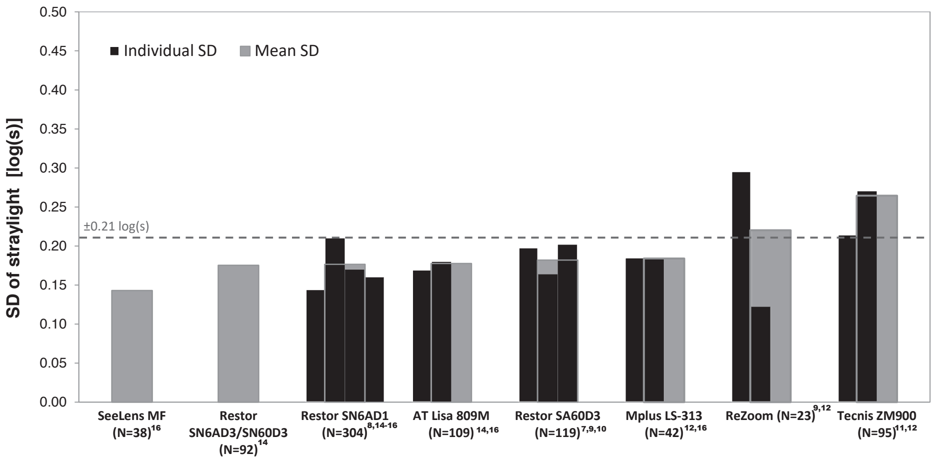

Figure 3. Standard deviation of log(s) for the studied IOLs. The black bars show the SD per study if the results were derived from different centers. The gray bars represent the pooled SD of the individual IOL models. The dashed line indicates the SD in the overall normal pseudophakic population.

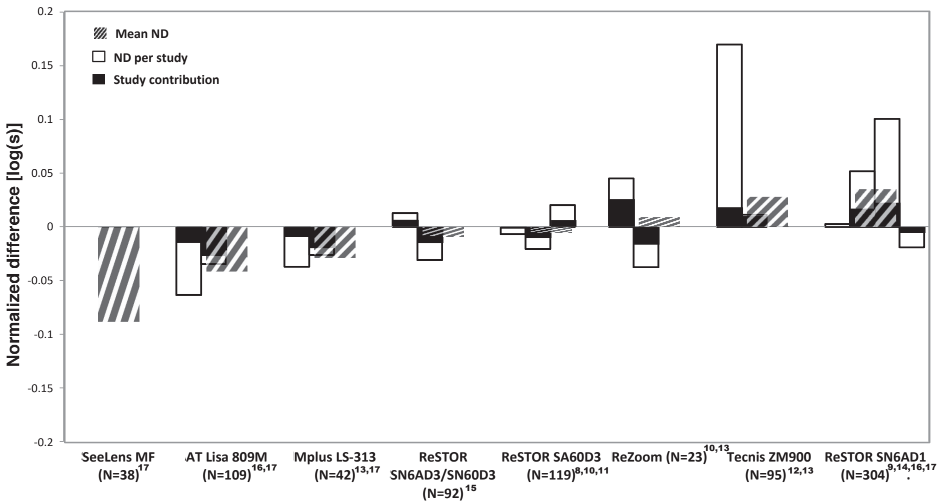

Figure 4. Normalized difference for each IOL group. Normalized difference shows to what extent a mean straylight result differs from the normative value. Note that the positive sign refers to straylight values above the norm. The gray bars describe the weighted mean normalized difference if more than 1 study was included; the empty bars indicate the mean normalized difference of an IOL group per study. The black bars give the contribution (weight) of each study to the mean normalized difference of the respective group by weighting over the sample size (the sum of black bars for a single IOL group equals the value of the respective gray bar).

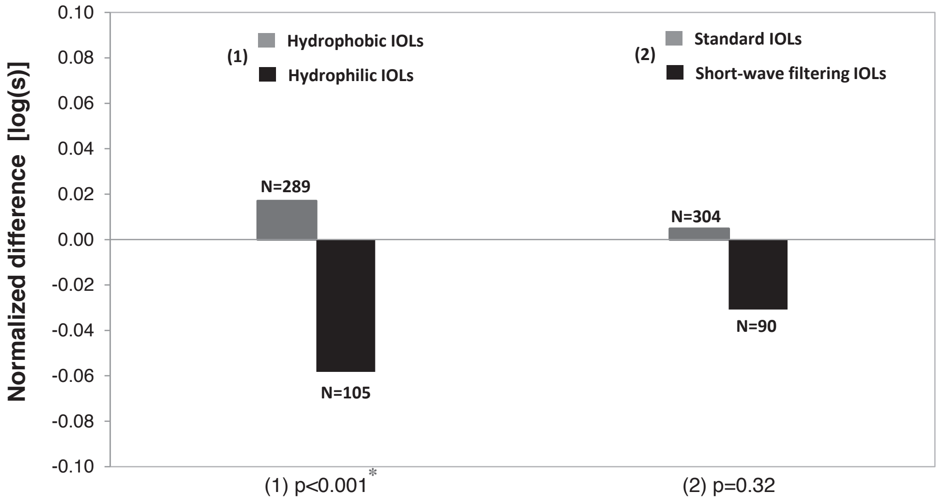

Figure 5. Normalized differences for different IOL material characteristics. Note that positive normalized differences indicate more straylight than the pseudophakic norm. The numbers (1 and 2) refer to the analysis of differences between the hydrophobic and hydrophilic materials and the standard and blue violet–absorbing IOLs, respectively (IOLs = intraocular lenses).

DISCUSSION

The current study shows that the type of implanted multifocal IOL affects the amount of postoperative straylight, and this can be partly explained by the differences in materials used for the IOLs, particularly when hydrophilic and hydrophobic IOLs are compared. In **Figure 4**, a clear distinction can be seen between hydrophilic and hydrophobic IOLs, with the hydrophilic IOLs (left side of figure) showing, on average, less postoperative straylight than the hydrophobic IOLs. When analyzed with the raw records from the 10 studies, the difference of 0.08 log(s) was statistically significant (P = .001). If this difference is compared with the effect of age on straylight in pseudophakic eyes (**equation 1**), it corresponds to a difference of nearly 2 decades. If the difference is compared with the logMAR scale, it corresponds to a difference of nearly 1 line (4 letters). Therefore, hydrophobicity appears a significant factor affecting intraocular straylight following multifocal IOL implantation. One earlier study also suggested that hydrophobicity increases straylight.[22] This study, however, investigated the effect of neodymium:YAG (Nd:YAG) laser capsulotomy on straylight. Although Nd:YAG laser capsulotomy is very efficient in reducing straylight, remnants can remain in the photopic pupil area and thus may have affected the study outcome.[20,22]

Straylight is the visual result of light scattered by inhomogeneity in the medium that light traverses. Extensive physical theory exists on the origin and properties of light scattering.[23] The relative size of the irregularities (*i.e.*, the ratio between size and wavelength) is an important parameter. If the ratio is (much) smaller than 1, scattering is isotropic but weak

(Rayleigh scattering). Larger particles cause an increase in scattering, especially in the forward direction.[23] The functional importance of particle size in human eye lenses was studied by van den Berg and Spekreijse.[24] The study found that particles with a radius of approximately 0.7 mm dominated forward light scatter, whereas particles much smaller than the wavelength (*e.g.*, single proteins) were more important at large angles (and dominate backward scatter).[24] These *in vitro* findings were in accord with *in vivo* straylight population study findings.[25] Similar to their existence in the crystalline lens, light-scattering particles may also exist in IOLs, according to several reports.[26,27] They can be large, seen as glistenings with the slit-lamp microscope,[27] or small, such as subsurface nanoglistenings.[28] A recent clinical study of the relationship between glistenings and straylight showed a significant, albeit not large effect.[29] Furthermore, another *in vitro* study demonstrated that the straylight effects of subsurface nanoglistenings is not significant.[B]

A clear difference can be found between the hydrophobic and hydrophilic materials in terms of surface roughness.[30] The difference between the average roughness of the acrylic hydrophilic IOLs (9.02 ±0.86 nm) and the acrylic hydrophobic IOLs (2.61 ±0.41 nm) was significant.[30] However, the values are so much smaller than the wavelength that these surfaces can be considered smooth surfaces and cannot be of significance in light scattering. This also supports our decision to include hydrophilic IOLs with a hydrophobic surface in the hydrophilic group.

Figure 2 shows that the individual mean log(s) values in most enrolled studies follow the norm for straylight in pseudophakic eye.[19] Moreover, the observed straylight age dependency in **Figure 2** underlines the necessity of using age correction when different age groups are compared. That was done and is presented in **Figure 4**, in which a significant variation is seen in the postoperative straylight in the IOL groups. Further subdivision led to a comparison of models within the hydrophobic and hydrophilic groups. Within these groups, the straylight differences between models were insignificant. **Figure 4** shows a difference of 0.12 log(s) in straylight between the models on the extreme ends (*i.e.*, Seelens MF versus Restor SN6AD1). The main difference between these IOLs is their material characteristics; *i.e.*, Seelens MF is an acrylate hydrophilic IOL and Restor SN6AD1 is an acrylate hydrophobic IOL. The difference in their optical designs seems to be minute. Both are diffractive apodized IOLs, although Seelens MF contains 12 diffractive zones versus 9 in the Restor SN6AD1. That these IOLs appear to be similar in their optical designs underlines the potential importance of hydrophobicity as a factor of postoperative straylight elevation. However, it must also be noted that the Seelens data come from 1 center in contrast to the multicenter results of the Restor SN6AD1.

A direct comparison in straylight between hydrophilic and hydrophobic IOLs was also made by Maurino et al.16 The Restor SN6AD1 and AT LISA 809M IOLs were studied, and the mean straylight value was, on average, lower in the hydrophilic group. De Vries et al.[14,15] studied apodized diffractive IOLs of the same manufacturer. In 1 study, the only difference was a spherical versus an aspheric design,[15] whereas in the other study, an addition power was the parameter that differed between the IOL groups.[14] No difference in ocular straylight was found between the evaluated IOLs. This can be expected since aberrations and refractive errors relate to a different part of the point spread function than ocular straylight.[2] A comparison of 3 types of multifocal IOLs was performed by Ehmer et al.[13] The Tecnis ZM900 showed more straylight than the Rezoom and Mplus LS-313, with relatively close outcomes between the refractive IOLs. However, the analysis was done without age adjustment, which could result in relatively better performance of the hydrophilic Mplus as the highest age was found in this group.

It is well known that not every patient is a good candidate for a multifocal IOL.[31] Therefore, patient selection requires a stricter approach than in the case of a monofocal IOL. This might lead to a patient selection bias, with a reduced SD and better postoperative straylight level for the multifocal population. However, it is well known that adverse photopic phenomena are more often reported with multifocal IOLs than with monofocal IOLs.[32] Since a multifocal IOL provides near and distance correction simultaneously, the secondary (out of focus) focus causes a blur circle around bright points. This blur circle is of the order of 10 minutes of arc in diameter. This is very small and, as a consequence, not a contributor to disability glare. Yet it is very noticeable to the patient and may lead to complaints. This phenomenon may confuse the issue of disability glare as studied presently. In the current review, the mean straylight value was 1.18 ±0.19 log(s), which was lower than the value in normal pseudophakic eyes; *i.e.*, 1.21 ±0.21 log(s).[19] The difference was even greater considering that the normative population included patients with multifocal IOLs. When types of IOLs are compared, care must be taken that patient selection does not differ, otherwise an inclusion bias can result in misleading interpretation of data. Besides the significance of the difference between IOL materials, inclusion bias might be a factor when multifocal and monofocal IOLs are compared. Five studies have reported the postoperative log(s) of multifocal and monofocal IOLs. Cerviño et al.[8] and Wilkins et al.[12] did not find a significant difference, whereas de Vries et al.[9] and Peng et al.[11] reported lower straylight values in the monofocal group. Moreover, Hofmann et al.[10] found a rather high difference of 0.08 log, also in favor of the monofocal group, but the difference was not statistically significant.

The wavelength dependency of straylight has been studied. The conclusion that yellow sources of light, in contrast to green and blue light, might attenuate disability glare has been presented.[33] However, there is no agreement about whether yellow-tinted IOLs might reduce postoperative glare.[34,35] In the current review, the effect on straylight of blue violet light–filtering and standard multifocal IOLs was studied. The mean result showed better straylight by 0.04 log(s) in the group of IOLs with short wave–absorbing chromophores in their material, but this difference was not statistically significant. In the study by Coppens et al.,[36] it was shown that ocular straylight can be modeled by 3 components with different wavelength dependencies. The base component showed the classic blue dominance of light scattering. Young and well-pigmented eyes may show this characteristic. With less pigmentation (as in white patients), a pigmentation-dependent component is added, dominating at long wavelengths. As a third component, an age-dependent addition was found with low wavelength dependency. Therefore, whether tinted IOLs might improve postoperative straylight may depend on a characteristic of an individual patient. As the individual characteristics within the studied populations were not available, the difference of 0.04 log(s) between the blue violet light–filtering and standard IOLs should be interpreted with caution.

In conclusion, the review showed that straylight of hydrophobic and hydrophilic multifocal IOLs differs significantly. The higher straylight level in the hydrophobic IOLs may originate from particles present in their material, since the observed surface roughness causes a negligible effect on light scattering. Although the optic design appears to be an important factor, if the hydrophobicity criterion is taken into account, only small differences between multifocal IOLs are seen.

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