

Journal of Biomedical Optics

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Abstract. This study presents a method for measuring scattering in explanted intraocular lenses (IOLs). Currently, determining scattering in IOLs is usually performed by Scheimpflug cameras and the results are expressed in the units used by this apparatus. The method we propose uses a spectrophotometer and this makes it possible to measure the total transmission of the IOL by using an integrating sphere; the direct transmission is determined by the double-beam mode. The difference between these two transmissions gives a value of the scattering in percentage values of light lost. In addition, by obtaining the spectral transmission curve, information about the most scattered wavelengths is also obtained. The IOL power introduces errors when directly measured, particularly with high powers. This problem can be overcome if a tailor-made cuvette is used that shortens the distance between the IOL and the condensing lens of the spectrophotometer when the IOL powers are below 24 diopters. We checked the effectiveness of this method by measuring the scattering of three explanted IOLs from cornea donors. This method, however, does not make it possible to ascertain whether the scattering measured is caused by surface light scattering or internal light scattering. © The Authors.

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Keywords: scattering; intraocular lens; spectral transmission; glistening.

Paper 140624R received Sep. 29, 2014; accepted for publication Nov. 21, 2014; published online Dec. 24, 2014.

1 Introduction

The biomaterial used in the manufacture of intraocular lenses (IOLs) implanted in cataract surgeries can undergo a progressive degradation. This can be caused by the appearance of so-called snowflakes or different deposits or precipitates adhering to the surface or to changes in the bulk properties of the IOL material. Such degradation can modify the optical properties of the IOL, bringing about a decrease in the IOL transmission or scattering of the light that passes through the IOL. A decrease in transmission results in less light reaching the retina and greater scattering translates into a decrease in direct light reaching the retina which forms the image. Increasing the diffused light on the retina can also cause halos or glare. These effects play a negative role in the patient's vision as they can produce a decrease in the contrast sensitivity function and even a lower visual acuity.¹

However, scattering in IOLs is a difficult problem to analyze. At first, one must distinguish between surface light scattering and glistenings.² Glistenings are fluid-filled microvacuoles that form inside the intraocular lens optic when the IOL is in an aqueous environment, thereby producing an internal light scattering which is difficult to distinguish from surface light scattering.²⁻⁴

Werner et al.,⁵ when analyzing some one-piece hydrophobic acrylic IOLs removed from cadaver eyes, demonstrated that surface light scattering significantly increased when compared with scattering in IOLs that had not been used, but their transmittance did not vary. Although the controversy continues, it seems that the cause of light scattering on the surface of hydrophobic

acrylic IOLs (referred to by some authors as whitening) is due to a trace of water molecules that infiltrate the optic.⁶ This also occurs in hydrophilic acrylic IOLs.⁷ The deposits that cause opacification can be found on the optic surface or inside the IOL substance. Histochemical methods as well as surface analyses have demonstrated that the composition of the deposits is partly calcium and phosphate.⁸⁻¹⁰

Regardless, whether the scattering is interior (glistening) or surface light scattering (whitening), the visual consequences are mainly the formation of halos or glare on the retina that can cause a decrease in contrast. Therefore, it is important to be able to accurately evaluate light scattering.

The most used method for measuring surface light scattering is with the different models of the Scheimpflug camera, i.e., EAS-1000 (Nidek, Inc.),^{1,2,4,5} Pentacam HR^{11,12} (Oculus) y C-Quant¹² (Oculus Optikgeräte GmbH). However, each model registers the results in different units, so one can compare the measurements relatively performed with the same apparatus, but not those determined with different models. Furthermore, it is difficult to evaluate the total amount of scattered light. For example, the EAS-1000 expresses the results in computer compatible tape (CCT) units. This is a measure of brightness or intensity of reflected (scattered) light on a scale of 0 (black) to 255 (white). The Pentacam HR quantifies the IOL densitometry on a scale of 0 to 100, where 0 refers to no opacity and 100 refers to total opacity. The difference between the Pentacam HR and the C-Quant is that the measures of the former are determined in mydriasis while those of the latter are determined in miosis.

Total transmission measurement is performed in all cases using a spectrophotometer (usually the PerkinElmer Lambda

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35 UV/VIS), which is equipped with an integrating sphere that gathers all the light transmitted by the IOL. Because it uses an integrating sphere, both direct and scattered light are collected by the detector; therefore, there is only a decrease in the transmission when the IOL presents opacities that entirely prevent the light from passing through. Indeed, this occurred in the study by Michelson et al.¹ in which a decrease in transmission was found when the IOLs, which had been explanted because of opacification, were analyzed using a spectrophotometer with an integrating sphere. On the contrary, as we pointed out above, Werner et al.⁵ found variation in the scattering, but not in the transmittance, when they studied surface light scattering in IOLs removed from cadaver eyes.

In this study, we determined both the scattering and the spectral transmission with just one spectrophotometer, so that the determination of scattering would be objective and would not depend on the apparatus performing the measurements. We used the double beam (DB) mode on the spectrophotometer and then the single beam (SB) mode, i.e., with the integrating sphere, to evaluate the scattering. In the first case, only the direct light that reaches the detector is registered and the scattered light is lost. In the second case, with the integrating sphere, all the light that passes through the IOL is measured, both the direct and scattered light. The difference between both measurements quantitatively shows the light lost due to scattering. In the case of direct light (DB), however, it would be necessary to study and minimize the influence that the IOL power can bring about on the measurements because Akinay et al.,¹³ when comparing the spectral transmission measurement of the IOLs with an integrating sphere and direct light (SB), reported the effect that the IOL power has on the direct measurement. Another advantage of this method is that when the complete spectrum is obtained of both the visible and the ultraviolet A and B, we can determine which wavelengths are the most scattered in the different cases.

2 Methods

2.1 Material

A PerkinElmer Lambda 35 UV/VIS spectrophotometer (PerkinElmer, Waltham, Massachusetts) was used for the measures in this study. The SB mode was used to measure total radiation, i.e., with the integrating sphere (LabSphere RSA PE 20, Perkin-Elmer) with a 50-mm aperture [Figure 1(a)]. The DB mode was used to measure direct radiation with the aid of two detectors, one for the sample and the other for reference purposes [Fig. 1(b)]. A holder, which was tailor made to contain the IOLs, was inserted into the quartz cuvette [Fig. 1(a)] which was filled with a balanced salt solution (BSS). Specifically, BSS was used for reference purposes by introducing the holder, without the IOL, into the cuvette filled with BSS.

As Fig. 1(a) shows, when the integrating sphere is used, all the radiation that passes through the IOL, both direct and scattered, is collected by the detector. However, when the DB mode is used [Fig. 1(b)], the detector only collects the direct light and the scattered light is lost.

2.2 Effects of Lens Power on Transmittance

The powers of the IOLs used in cataract surgery can vary within a wide range. The most common are usually around 21 diopters (D), but they can range from 10 to 30 D. This makes no difference in the case of measures performed with an integrating

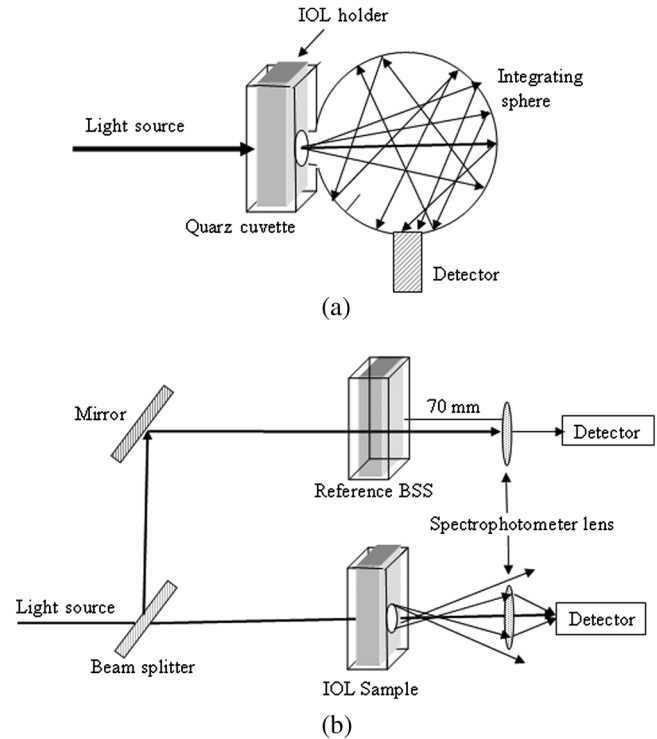


Fig. 1 Diagram of spectrophotometer measurements. (a) Integrating sphere mode (total transmission). (b) Double beam mode (direct transmission).

sphere, since in spite of the beam of light refracted by the IOL opening to a greater or lesser degree, all the radiation penetrates into the sphere and, therefore, the measurement does not depend on the power of the lens. On the other hand, as Akinay et al.¹³ previously reported, the effect of the IOL power can prove to be considerable in the case of DB measurements. As Fig. 1(b) shows, if the IOL power is high, as the focal distance is very short, the light beam opens up so much that part of the radiation does not reach the spectrophotometer condenser lens and consequently it is not detected. This would obviously produce an artefact when measuring scattering as the difference between the measurement with an integrating sphere and a direct DB measurement would not be exclusively due to scattering but rather that there could be losses caused by the high powers. A way of solving this problem, as Akinay et al.¹³ pointed out, is by changing the distance between the IOL and the spectrophotometer condenser lens that focuses the light in its photodetector. As Fig. 1(b) shows, the distance between the IOL and the spectrophotometer lens is 70 mm; to reduce this distance we designed a new holder that shortens it to 15 mm. Figure 2(a) shows this new holder which exactly fits into the spectrophotometer and has the precise measurements to house the quartz cuvette [Figure 2(b)]. At the back of the holder there is a small screw for accurately positioning the height of the cuvette. Two units of this new holder were constructed, one for reference purposes and the other for the sample.

2.3 Intraocular Lenses

The type of material the IOLs are manufactured from can influence their spectral transmission; however, the variations in the visible spectral region are negligible and only some differences can be observed in the ultraviolet region mainly caused by the

type of ultraviolet filter incorporated in them.¹⁴ Only Oculaid intraocular lenses (Ophtec, Groningen, The Netherlands) were used in this study. The material is a hydrophilic acrylic copolymer with an ultraviolet (UV) inhibitor ($\lambda < 400$ nm). However, these lenses let some ultraviolet radiation through, so the measurements can provide information about light scattering in this area. The powers of the IOLs were 14, 19, 21.5, 26, and 30 diopters. As an example of the method, three explanted IOLs made by different commercial brands with powers of 18, 21.25, and 23 D were used. These IOLs come from cadaveric cornea donors, so even though it would be possible to deduce the manufacturer by the IOL shape and type of haptics, because we cannot do so with certainty, we shall refer to these IOLs only by their power. We measured their power with an optical lens meter (Magnon LM350) by placing a diverging ophthalmic -10 D lens in the lens holder. Physiological saline solution (NaCl 0.9%) was added to the concave side of the lens where the IOL was submerged to be measured. This device has two advantages: on the one hand, the IOL is measured in a liquid medium which is how the IOL behaves *in vivo*, and on the other hand, the -10 D ophthalmic lens made it possible to measure positive powers higher than the lens meter could

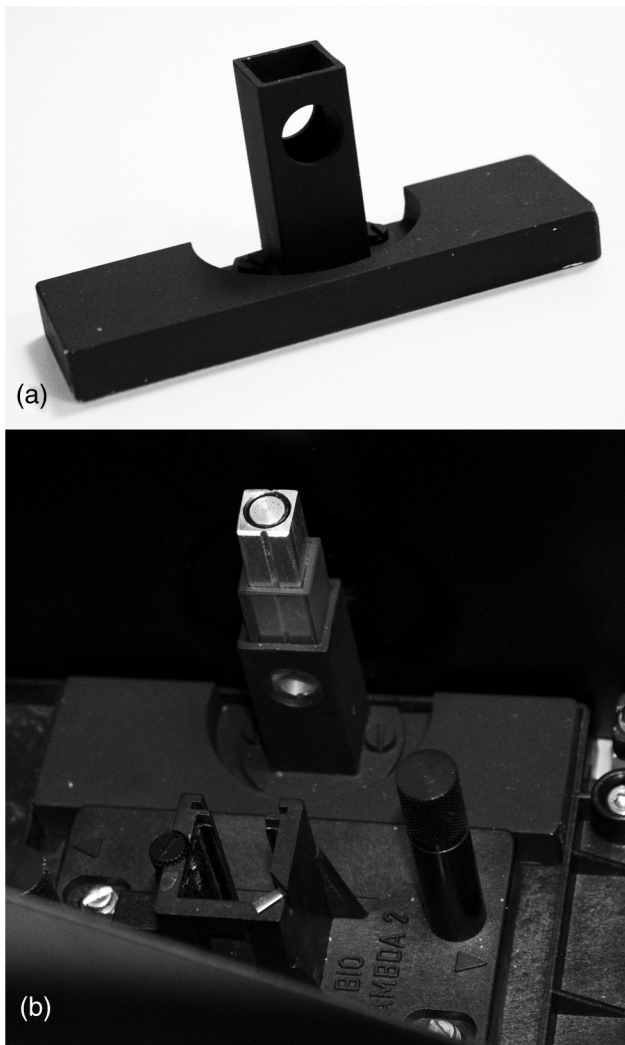


Fig. 2 (a) Cuvette holder designed to decrease the distance between the intraocular lens (IOL) and the spectrophotometer condenser lens. (b) Cuvette holder in its position in the spectrophotometer.

under normal conditions. With regard to the material these three IOLs are made of, we can only say that it is not PMMA as none of the three are rigid, so they are acrylic or silicone. The 21.25 D IOL has a yellow filter.

2.4 Data Analysis

All the measurements were performed at room temperature as it has already been demonstrated¹³ that there is no significant variation in the result of the measurements when they are performed at room temperature 35°C . The PerkinElmer Lambda 35 spectrophotometer is accurate within $\pm 1\%$ transmittance, so any difference greater than 1% could be optically considered significant. Nonetheless, as placing the IOL in the holder could cause a slight misalignment which could cause small variations in transmission in the case of surface scatter, all the IOLs were measured three times each, regardless of the type of scattering. In addition, it should be taken into account that a small difference in transmission does not necessarily mean a decrease in the patient's vision.

3 Results

3.1 Measurement of Total Radiation

Measurement of the total radiation that passes through the IOL is performed with an integrating sphere, i.e., in the SB mode on the spectrophotometer; in this way, all the radiation that passes through the IOL is registered. Figure 3 shows the transmission of the six IOLs with different powers that were used in the study. The samples were placed in the holder and submerged in the cuvette containing BSS; the determination was carried out at room temperature.

3.2 Measurement of Direct Radiation

The measurement of direct radiation was carried out in the spectrophotometer DB mode so that the detector would only register the light reaching it directly after passing through the IOL and the scattered light would be lost. In this case, the distance between the position of the IOL and the condenser lens was that of the spectrophotometer, i.e., 70 mm. Figure 4 shows the direct transmission of the six IOLs. As in the previous case, the samples were placed in the holder and submerged in the cuvette containing BSS; the measurements were performed at room temperature.

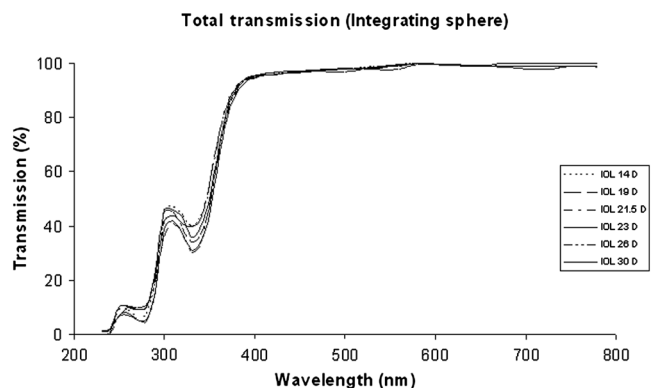


Fig. 3 Spectral transmission curves of the six IOLs that were used, measured in the integrating sphere mode (total transmission).

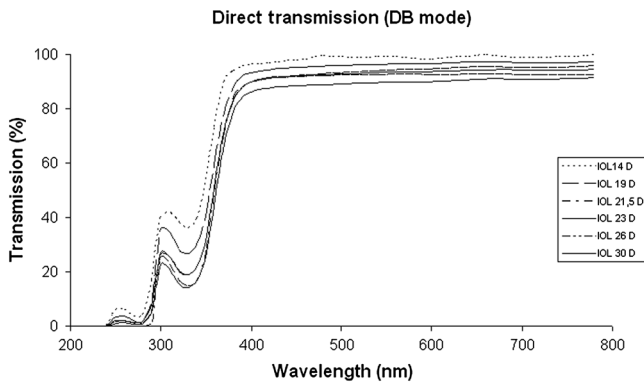


Fig. 4 Spectral transmission curves of the six IOLs that were used, measured in the double beam (DB) mode (direct transmission) and at the normal distance 70 mm between the sample (IOL) and the spectrophotometer lens.

3.3 Measurement of Direct Radiation at a Short Distance (15 mm)

With a view to minimizing the effect the IOL power has on measurement, we used a tailor-made holder (Fig. 2) to reduce the distance between the sample and the spectrophotometer condenser lens, and the distance was only 15 mm rather than the original 70 mm. Figure 5 shows the results for this distance for which the measurement conditions were the same as the previous cases.

3.4 Measurement of the Spectral Transmission of the Explanted Intraocular Lenses

In this section, the spectral transmission of three IOLs explanted from cadaveric cornea donors was determined. Therefore, these IOLs presented no obvious deterioration due to opacification or deposits and consequently if there was any loss of light through scattering, it could only be due to ageing. Figure 6 shows the spectral transmission of these three IOLs measured with an integrating sphere and in the direct mode (DB), from both the spectrophotometer sample-lens distance (70 mm) and the new, shorter distance (15 mm).

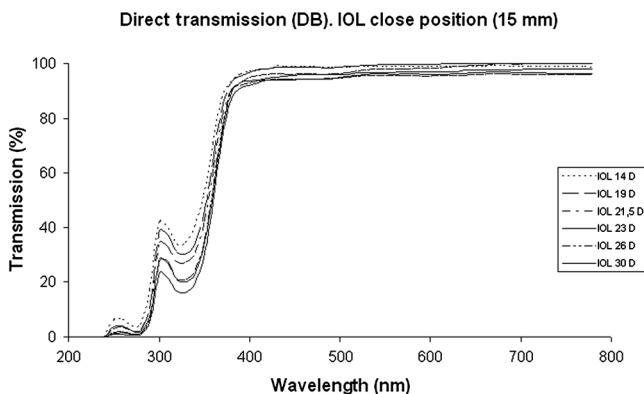


Fig. 5 Spectral transmission curves of the six IOLs that were used, measured in the double beam mode (direct transmission) and at the new distance (15 mm) between the sample (IOL) and the spectrophotometer lens.

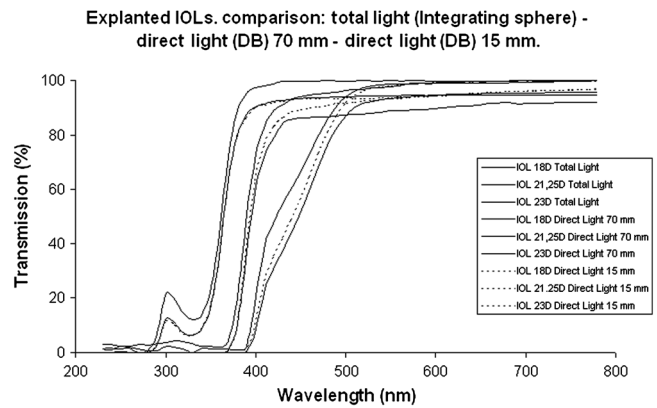


Fig. 6 Spectral transmission curves of the three IOLs that were explanted from cornea donors, measured with the integrating sphere, double beam at 70 mm and double beam at 15 mm.

4 Discussion

As mentioned above, Akinay et al.¹³ previously reported the differences between measuring the spectral transmission of intraocular lenses with an integrating sphere (SB mode) and directly (DB mode): they recommended using the integrating sphere in general and only using the DB mode in the case of low power IOLs. In fact, the integrating sphere mode¹⁴⁻¹⁶ is always used for ascertaining not only the shape of the spectral transmission curve, but also the total amount of light that passes through the IOL. The integrating sphere mode is also used for human¹⁷ and pig¹⁸ crystalline lenses. On the other hand, Boettner and Wolter¹⁹ in their classic study performed ocular media transmission measurements in both modes. In the case of the lens, they state that they flattened it slightly without breaking the lens capsule. The reason for flattening the lens surface was to remove as much of the optical lens effect as possible. These authors¹⁹ termed “total transmission” as the measurement made with an integrating sphere and “direct transmission” as the measurement made in the DB mode.

In our study, we verified that measuring with the integrating sphere gives similar results, regardless of the IOL power. Figure 3 shows that the six IOLs we measured practically transmitted 100% of the visible spectrum (380 to 780 nm). It shows a small scattering in the UV that is of little consequence as the IOLs are made to transmit in the visible spectrum and not in the UV, so the vast majority of IOLs also comprise ultraviolet filters.

Figure 4 shows the spectral transmission of the six IOLs, but they were obtained in this case in the DB mode, i.e., direct transmission and using the spectrophotometer alone; in other words, the distance between the IOL and the condenser lens was 70 mm. It shows that the transmission depends on the IOL power, and the highest transmission corresponds to the lowest power (14 D) and the lowest to the highest (30 D). This result is logical since the highest power opens the beam up so much that part of it cannot penetrate into the spectrophotometer lens and consequently it registers a lower value. This is an artefact in measuring scattering. As Akinay et al.¹³ suggested, this problem could be avoided by reducing the distance between the position of the IOL and the spectrophotometer lens. By using the tailor-made device (Fig. 2), we performed the measurements in DB mode but with a distance of 15 mm between the IOL and condensing lens. Figure 5 shows the results: the differences in

transmission between the diverse powers are clearly lower and in some cases are indistinguishable.

With a view to more objectively analyzing these results, we calculated the amount of total light in the visible spectrum that these IOLs transmit under the different measuring conditions.

To determine the total transmission of the visible spectrum of an IOL, first the tristimulus values (X, Y, and Z) were calculated in accordance with the following equations:

$$X = \sum_{\lambda} \bar{x}(\lambda)S(\lambda)\tau(\lambda),$$

$$Y = \sum_{\lambda} \bar{y}(\lambda)S(\lambda)\tau(\lambda),$$

$$Z = \sum_{\lambda} \bar{z}(\lambda)S(\lambda)\tau(\lambda),$$

where $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are the color-matching functions of the standard observer, $S(\lambda)$ is the spectral distribution of the source (in this case illuminant D65 or solar illumination), and $\tau(\lambda)$ is the spectral transmittance of the IOL. The value of the tristimulus Y indicates the lightness or luminance in the case of a surface and the transmittance of the filter or lens in this case (IOL). Then, the transmission (T) in the visible spectrum (380 to 780 nm) was calculated following the equation:

$$T = \frac{\sum_{\lambda} \bar{y}(\lambda)S(\lambda)\tau(\lambda)}{\sum_{\lambda} \bar{y}(\lambda)S(\lambda)}.$$

Table 1 shows these results for the different ways in which the IOLs were measured. It illustrates, as previously mentioned, how when an integrating sphere is used the power of the IOL makes no difference and the transmission is excellent for all the IOLs, reaching practically 100% in all the cases. When the measurement is direct, i.e., when using the DB mode, and under the usual conditions of the spectrophotometer, i.e., with a distance of 70 mm between the IOL and the condenser lens, the amount of light transmitted that the spectrophotometer registers decreases by as much as 9% for a 30 D power and hardly alters at all for the lower power (14 D). These results are similar to those obtained by Akinay et al.,¹³ although

Table 1 Transmission in the visible spectrum of the six intraocular lenses (IOLs) measured using the three modes described.

Power lens	Integrating sphere transmission	Direct measure 70-mm transmission	Direct measure 15-mm transmission
30 D	99% ± 1	90% ± 1	96% ± 1
26 D	99% ± 1	93% ± 1	96% ± 1
23 D	99% ± 1	93% ± 1	97% ± 1
21.5 D	99% ± 1	94% ± 1	98% ± 1
19 D	100% ± 1	96% ± 1	100% ± 1
14 D	99% ± 1	99% ± 1	99% ± 1

those authors only mention the transmission variation for two wavelengths (450 and 850 nm) and not for the whole visible spectrum. The transmission decreases are much less pronounced when the distance between the IOL and the condenser lens is 15 mm. In fact, we can state that for IOLs with powers lower than 24 D, this transmission decrease compared with that of the integrating sphere is practically nonexistent. Although the decrease is small for 26 and 30 D IOLs, it is just discernible. In view of the above, we can deduce that by decreasing the distance between the IOL and the spectrophotometer condenser lens, the transmittance measured in an IOL that has not been used is the same regardless of whether the integrating sphere or the direct measurement (DB) is used, so long as the power is equal to or lower than 24 D. This means that scattering can be evaluated in these lenses by determining the difference between the transmission in the visible spectrum measured with an integrating sphere (total transmission) and with the DB (direct transmission). Moreover, by obtaining the complete transmission curve, the wavelengths that are most scattered can be determined if necessary.

The IOLs implanted in cataract surgery usually have a power of around 21 D. Indeed, at our center, Fisabio Oftalmología Médica (FOM), 1,933 cataract surgeries were performed between January and August 2014; 1557 of these were for implanting IOLs with a power ranging from 18 to 24 D, i.e., 80%. One hundred and eighty-two IOLs with powers higher than the 24 to 31 D range were implanted which is 10%, and those with a power lower than 18 D also comprised 10%. This suggests that in most cases it is feasible to use this method to determine scattering.

With a view to testing this possibility, we performed some measurements of three IOLs with 18, 21.25, and 23 D powers that had been explanted from cornea donors. Figure 6 shows these results in which the transmission curves are depicted for the three IOLs determined with an integrating sphere, with direct measurement (DB) at 70 mm, and direct measurement (DB) at 15 mm. It can be deduced from these curves that the greatest differences always arise for short wavelengths (between 400 and 500 nm). In addition, in order to quantitatively evaluate scattering, we determined the total transmission in each case in the visible spectrum. Table 2 shows these results in which, once again, the difference between performing direct measurements at 70 and 15 mm from the spectrophotometer lens can be seen. The interesting point is that in accordance with what was previously determined, the difference between what was measured with an integrating sphere and with direct measurement at 15 mm yields a quantitative scattering value.

Table 2 Transmission in the visible spectrum of three explanted intraocular lenses (IOLs) measured using the three modes described.

IOL power	Integrating sphere transmission	Direct measure 70-mm transmission	Direct measure 15-mm transmission
23 D	98% ± 1	86% ± 1	93% ± 1
21.25 D	97% ± 1	91% ± 1	96% ± 1
18 D	100% ± 1	94% ± 1	94% ± 1

Thus, the 23-D IOL has a loss of around 5% due to scattering and the 18-D IOL, 6%, while the 21.25-D IOL presents practically no loss. Let us bear in mind that these IOLs were not explanted due to problems with opacification or deposits, but rather that they came from cornea donors, so we can only say that they were used and aged IOLs. Accordingly, it can be deduced that the 21.25-D IOL was used very little as its total and direct transmission virtually coincide. The 18- and 23-D IOLs present some small losses due to scattering, but much fewer than those demonstrated by Michelson et al.¹ when they analyzed IOLs explanted because of opacification. Nonetheless, it is difficult to quantitatively compare their results because these authors¹ report their results in CCT units.

Although it is not the aim of the present study, it is interesting to note that as our results show the main differences brought about by short wavelengths, one might think that the predominant scatter is Rayleigh because of its dependence on the wavelength. This scatter would produce a diffusion of light over the whole retina causing a halo or glare that would affect contrast vision. However, if we take into account that deposits on IOLs cause the most amount of scattering, and that the particles that make up such deposits may be greater than the light wavelength, then Mie scatter would be present and forward light would predominate and would consequently mainly affect the fovea, thereby strongly affecting vision. Discerning the type of scattering caused by an aged IOL was not the aim of the present study, but it would be interesting to perform new measurements and study this process in depth in the future. To conclude, we present a method that makes it possible to quantitatively determine the amount of light scattered by an IOL using a spectrophotometer that has had the distance between the IOL and its condenser lens directly modified for measuring (DB). The total amount of light transmitted by the IOL is determined by using the integrating sphere mode on the spectrophotometer. The difference between the total and direct transmission provides the amount of scattering produced by the IOL. The wavelengths that are most affected by scattering can be deduced from the curve obtained with the direct measurement. This method, however, does not make it possible to discern between surface light scattering and internal light scattering.

Acknowledgments

The Càtedra Alcon-Universitat de València sponsored MC García-Domene's grant.

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