Comparison between an objective and a psychophysical method for the evaluation of intraocular light scattering

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In this study we present the comparison of the performance of two systems to measure intraocular scattering. Measurements were made by using a psychophysical system based on a brightness comparison method that provides a glare index and a physical system based on the double-pass technique, which gives an objective scatter index by measuring the optical quality of the eye. Three external diffuser filters that simulated different grades of intraocular scattering were used in subjects with normal vision. The two measured indexes showed a graded rise with increasing level of scattering. The discrimination ability obtained for both systems showed that they were able to distinguish among conditions ranging from normal to early cataracts.

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1. INTRODUCTION

The quality of the retinal image that the eye builds up from the external world depends on the aberrations of the eye's optical system, the scattered light that comes into the retina, which is called straylight, and the diffraction. Apart from diffraction, which is negligible for pupils that are larger than 2 mm, aberrations and scattering are the main factors that determine the quality of daily life vision. In general, the effect of optical aberrations could be summarized as a blurring of the retinal image that reduces the subject's visual acuity; meanwhile the straylight reduces the contrast of the retinal image [1,2] and produces a darker perception of the scene [3,4]. There is evidence that for eyes with high levels of scattering, the addition of a small amount of spherical aberration may slightly increase contrast sensitivity (CS) [5]; however, the combined effect of aberrations and scattered light on the quality of the retinal image needs further discussion.

Normal eyes do not have high levels of straylight, but conditions such as opacity of the eye media due to age, cataracts, or changes in the cornea produced by refractive surgery can cause greater straylight that leads to worse vision. In addition, intense light sources in the field of view produce more scattered light on the retina, increasing the effects of the above causes.

Different approaches to psychophysical evaluation of intraocular scattering assessed the effects of a glare source on visual functions. One of the first methods proposed was the measurement of the CS function with and without a glare source [6], which allows a light scattering factor to be computed [7]. In contrast, the brightness acuity tester (BAT) considers the evaluation of the visual acuity [8]. By means of the compensation comparison method and a flickering glare ring that adds a veil to a central bipartite test, the so-called *C*-Quant system determines the straylight produced by the flickering glare ring [9,10]. This last method is an improved version of the direct comparison method (see [11]), in which a ring-shaped glare source produces straylight on a dark background test region lightening it. This straylight is sequentially compared with the luminance of a stimulus in the same test region.

Recently, a new system has been developed to quantify intraocular scattering by means of the brightness comparison method (BCM) [12]. Though it is well known that brightness perception depends on retinal illuminance but also involves retinal and potentially cortical mechanisms [13,14], it has been shown that glare effects on brightness perception may be associated with veiling luminance when the stimulus is presented on a dark surround [3,4]. Although this relationship is highly nonlinear [3], BCM determines the brightness reduction of a central test due to a peripheral glare source using a suprathreshold task. Thus, the system evaluates ocular diffusion under conditions that are more similar to those in real life.

Intraocular scattering can also be measured by analyzing the point spread function (PSF), which describes the optical quality of the eye and shows how the light from a point-source object is spatially distributed onto the corresponding retinal image. The PSF can be objectively obtained from wavefront sensors, usually on the basis of Hartmann-Shack [15,16] and laser ray tracing [17], or by directly measuring the retinal image using the double-pass (DP) method [18]. This technique, which is based on recording the image of a point source object after reflection on the retina and a double pass through the ocular media, has been widely used to measure the eye's optical quality [19,20] in various situations of clinical interest, such as in the normal population as a function of age [21], in patients implanted with intraocular lenses [22] and in patients who have undergone laser-assisted in situ keratomileusis (LASIK) and photorefractive keratectomy (PRK) surgery [22,23]. DP images are affected by both ocular aberrations and scattering [24]. Recently, a new method was developed to estimate the magnitude of intraocular scattering from DP images by means of the objective scatter index (OSI), which computes the ratio between the energy in the outer parts of the DP image and the energy in the center of it [25,26]. This methodology has shown its ability to establish the degree of cataract development [27].

It is of a great interest to compare the results obtained by objective measurements with those obtained by more conventional psychophysical procedures that take into account the subject's perception. In addition, it is very important to prove the accuracy of psychophysical measurements through objective measurements. In this study, we compared the performance of the mentioned psychophysical method based on brightness comparison (BCM) with results from the DP system that objectively evaluates intraocular scattering in the eye. To perform this comparison, we decided to use external diffuser filters that simulate cataracts in subjects with normal vision [12]. The filters used allowed to achieve small differences of diffusion among them, which otherwise, i.e., considering real patients, would have been difficult to control. The controlled amounts of diffusion achieved corresponded to those found for low scattering conditions or early cataracts, since our goal was to compare both systems in their ability to discriminate between these values of diffusion.

2. MATERIAL AND METHODS

A. Psychophysical System

The BCM was based on a haploscopic arrangement that allowed us to determine the brightness reduction of a test when there was a steady glare source in the visual field. In this haploscopic layout, a mask was placed at a proper distance from the eyes so that each eye looked at only one of two semicircles (Fig. 1). The stimulus display was placed 55 cm from the observer's eyes. The experiment was carried out with the subject's head resting on a chin rest. The stimuli were presented on a 19" Samsung SyncMaster 955DF TRC monitor that was electronically modified to have high gray level resolution. The display was programmed on Matlab using the psychtoolbox [28,29].

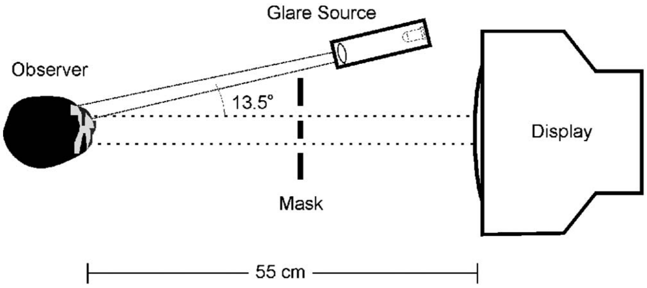

Fig. 1. Experimental setup of the BCM.

The stimuli were achromatic and each semicircle had a diameter of 5.6 deg. The luminance of one of the semicircles was 10 cd/m^2 (the reference stimulus: Rs), and it was seen by the eye that was wearing a specific diffuser filter. The other semicircle (the comparison stimulus) took a different value in each comparison. Values were selected from a range from 0.01 to 89 cd/m^2. This semicircle was seen by the other eye. The luminance of the surround was 0.04 cd/m^2. Two small circles were added to the stimuli in the nasal position to facilitate stereoscopic fusion, to avoid an overlap between the semicircles, and to achieve stabilization of the stimuli (Fig. 2).

An eccentrically placed glare source based on a tricolor light-emitting diode (LED) illuminated the eye that looked at the reference stimulus: "the evaluated eye." This source was placed at 13.5 temporal degrees. An illuminance of 40 lux was measured on the cornea's plane. To prevent glare beams from falling on the optic disk, the position of the source was 5 deg above the horizontal plane that contained the foveal line.

The matching luminance (Lm), i.e., the luminance of the comparison stimulus that matched the brightness of the reference stimulus, was assessed using a two-step procedure: a coarse adjustment to find the range for Lm, and a fine process to determine the value of Lm. The subject participated in a sequence of trials during each session. Each trial consisted of simultaneous presentation of the reference and comparison stimuli for 0.8 seconds. The subject then had to state which stimulus was brighter. The coarse adjustment was made using the method of the limits. The subject was shown 15 values of the comparison stimulus luminance in a range from 1.74 to 89 cd/m^2. The sequence was manipulated to make the task easier at the beginning, and then the difficulty increased. As a result, we had a first estimation of Lm. This first step also served as training for the subjects. In the second step, a QUEST adaptive method was adopted [30]. This Bayesian method requires an *a priori* value that was given by the Lm estimation from the first section. During this phase, the number of trials varied according to an *a posteriori* standard deviation value. When the standard deviation was lower than 0.1, the test concluded and Lm was set as the last value obtained. Subjects were not aware of these two experimental phases. We computed a glare index (GI) from the psychophysical BCM procedure as a stimulus luminance ratio:

$$\mathrm{GI} = \frac{\mathrm{Lr}'}{\mathrm{Lmg}} - 1, \qquad (1)$$

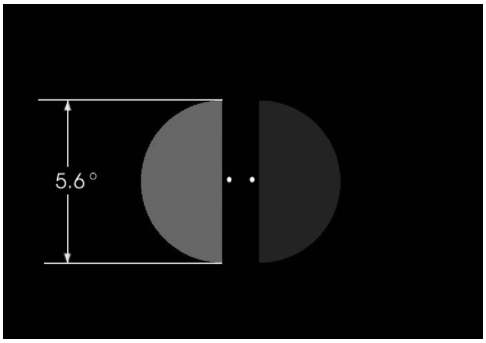

Fig. 2. Configuration of the stimuli in the BCM.

where Lr′ is the matching luminance under non-glare conditions and Lmg is the matching luminance under glare conditions. As it is simpler to work with positive values, we presented the data in terms of decimal logarithm of (GI + 1).

B. Objective System

The objective system used to quantify intraocular scattering was based on analyzing DP images. These images were recorded using a commercial instrument (Optical Quality Analysis System—OQAS, Visiometrics S.L, Spain) [31], which is represented schematically in Fig. 3. The instrument acquires the retinal image that corresponds to a point-source object by means of a CCD camera (CCD1), after reflection on the retina and a double pass through the ocular media. An optometer that consists of two lenses (L3, L4) and two mirrors (M2, M3), is used to measure the subject's defocus correction. The entrance pupil has a fixed diameter of 2 mm. The instrument also has an artificial and variable exit pupil (ExP) controlled by a diaphragm wheel, whose image is formed on the patient's natural pupil plane (see [24] for a more detailed description of the DP layout). Thanks to this asymmetric scheme of the DP technique layout, the OQAS system acquires DP retinal images and by Fourier transformation may directly compute the modulation transfer function (MTF), therefore allowing for the complete characterization of the optical quality of the eye, mainly degraded by higher-order ocular aberrations and scattered light. It must be taken into account that from asymmetric configurations of the DP system, both asymmetric and symmetric aberrations are correctly assessed meanwhile using symmetric DP systems, although the ocular MTF is also correctly computed, [32] asymmetric aberrations, such as coma, are lost in the DP images [33]. Furthermore, near-infrared light is used in the DP system because it is more comfortable for the subject and provides retinal image quality estimates that are comparable to those obtained with visible light [34]. In turn the use of green light, where the human visual sensitivity has its maximum peak, usually causes lasting post-images in the patients, which can be acceptable in laboratory measurements but not in a clinical environment.

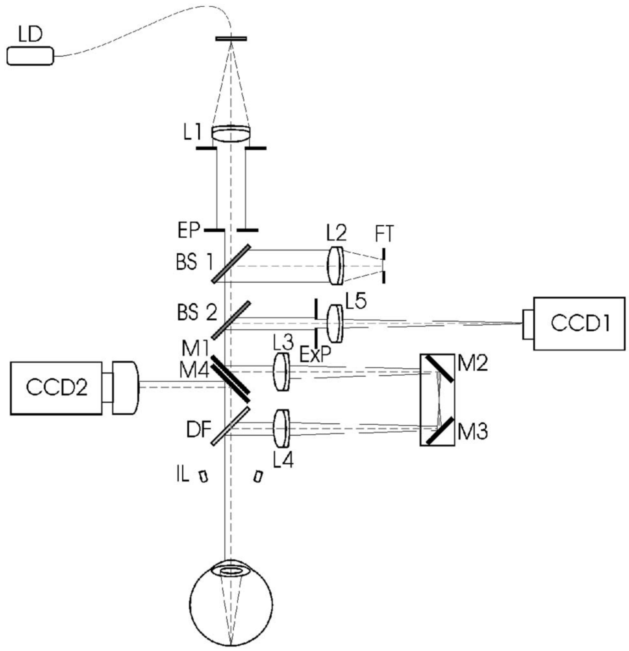

Fig. 3. Double-pass experimental setup (LD, laser diode; L1, L2, L3, L4, L5, lenses 1, 2, 3, 4, and 5; EP, entrance pupil; ExP, exit pupil; BS1, BS2, beam splitters 1 and 2; FT, fixation test; CCD1, CCD2: CCD, cameras 1 and 2; M1, M2, M3, M4, mirrors 1, 2, 3, and 4; DF, dichroic filter; IL, infrared LED).

From each DP image, the OSI can also be calculated [27], thus providing an estimation of the amount of ocular scattering. This parameter is computed as the ratio between the amount of light recorded inside an annular area between 12 and 20 mins of arc and that recorded within 1 minute of arc of the central peak (Fig. 4). A similar methodological approach was proposed by Westheimer and Liang [35], who measured an index of diffusion strongly tending to increase with age. The choice of the angles from which OSI is computed in the OQAS is based on the results obtained in a previous study [27], in which authors found a maximum correlation between OSI values and a standard cataract gradation (LOCS III) using this configuration in patients with different grades of cataracts. On the other hand, recent studies also suggest the usefulness of the OSI parameter in the clinical prediction of intraocular scattering [25,26]. In general, values of OSI below 1 are usually linked to eyes with very low scattering, OSI values between 1 and 3 correspond to older eyes with associated scatter of an early cataract, OSI values between 3 and 7 correspond to developed cataracts that should undergo surgery, and OSI values higher than 7 correspond to eyes with severe cataracts [27].

In this study, OSI was calculated by averaging six DP images that were acquired sequentially. Furthermore, the physical measurements were carried out at the best focus position in order to obtain the best retinal image and using an exit pupil diameter of 4 mm.

C. Filters

We used commercial filters to simulate different degrees of diffusion. The Black Pro Mist 1 (BPM1) and the Black Pro Mist 2 (BPM2) from Tiffen, which are usually used in photography, showing physical properties similar to those of early cataracts [12,36]. Furthermore, we used the filter Cinegel 3020 (C3020) from Rosco, which is commonly used in lighting design and

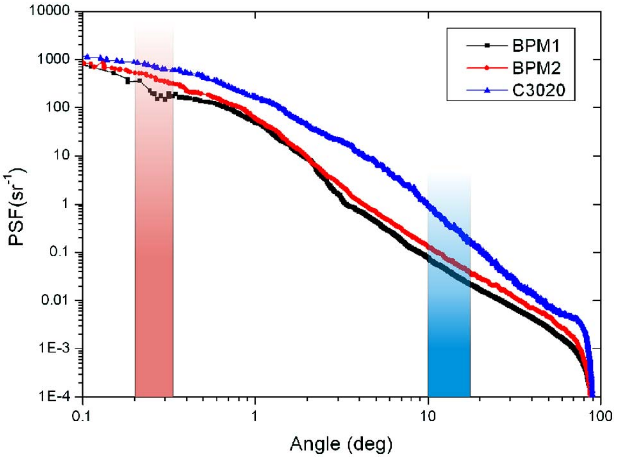

Fig. 4. (Color online) PSF of the filters BPM1, BPM2, and C3020. Shaded area on the left indicates part of the components taken into account to calculate OSI. Shaded area on the right indicates which are the components assessed by the BCM.

has properties similar to a more advanced cataract. A scatter meter described in a previous paper [12] was used to obtain the PSF of the filters. This first characterization of the filters showed a graded increase of the energy distribution in the peripheral areas taken into account for each system. Figure 4 shows the PSF data obtained for the three filters. It is possible to see the increase of the effects introduced by the filters as they pass from BPM1 to BMP2, and from BPM2 to C3020, in the range between 0.1° and 90°. It was not possible to obtain diffusion data for angles less than 0.1°. However, we determine if there is a crossing of the curves from an analysis of the filters transmittances. The C3020 has a total transmittance of 88%; however its direct component (measured for angles below than 0.1°) is only 13%. This value is much lower than the 57% corresponding to BPM1 and the 44% corresponding to BPM2. This indicates that for angles less than 0.1°, the PSF's curves should cross, leaving the BPM1 curve slightly above the BPM2 curve and both curves well above the C3020 curve. This analysis is consistent with the expected behavior in these filters about their energy distribution.

The straylight value (S) was also determined as $S = \text{PSF} * \theta^2$. According to the de Wit and colleagues study [36], any kind of cataract has a similar behavior for $S(\theta)$ around 10 degrees, with an approximate PSF slope of –2.12. We selected those filters because they responded to that pattern. Table 1 shows the S-values at 10° and the slopes of the straight lines of PSF between 3° and 30° of the three filters. The transmittances were also measured at 0° for the three tested filters (Table 1) and showed high values, which was also an appropriate condition for simulating cataracts [36]. Other filters were characterized and discarded for not having any of these conditions.

On the other hand, we also took into account a characterization of the effects of the filters in the functional vision of the subjects, by means of visual acuity and contrast sensitivity (CS). According to previous characterization, BPM1 and BPM2 did not produce a reduction in the uncorrected visual acuity (UCVA), while CS was affected by a mean reduction of 5% [36]. In the case of the C3020 filter we measured the UCVA in seven normal subjects finding an average value of 1.7 whereas when the subjects wore the filter, the UCVA fell to 1.2. In addition, a CS reduction of 32% was found at a low spatial frequency (3 cycles per degree) and a reduction of 54% for a high spatial frequency (18 cycles per degree). These values are in agreement with those obtained by Elliot and Situ [37] evaluating early cataracts for small (57%) and large letters (28%). The null or minimal reduction of UCVA and CS found in the BPM1 and BPM2 filters agreed with the measurements made in eyes with early cataracts [36,37], while the values for the filter C3020 were less than the maximum limit values of UCVA and CS needed to diagnose a cataract [38]. Filters were placed at 35 mm from the eye in the DP system and at 23 mm from the BCM system. However, one must take into account that the retinal straylight distribution coming from the filter is not significantly affected by the distance between the filter and the eye if the glare source is relatively far away from the eye and the filter dimensions are large enough [36].

Table 1. Transmittances (Mean ± Standard Deviation) of the Three Filters Used[a]

Diffuser	Transmittance	$S(10)$	Slope of the PSF ($3^\circ - 30^\circ$)
BPM1	0.706 ± 0.003	9.95	–2.15
BPM2	0.648 ± 0.012	12.97	–2.43
C3020	0.879 ± 0.006	57.36	–2.89

[a] The corresponding $S(10)$ and slope of the PSF ($3^\circ - 30^\circ$) are also shown.

D. Subjects and Conditions

Ten young subjects (30.5 ± 5.6 years old, mean± standard deviation) participated in the study. All of them had normal vision without glasses: their decimal UCVA was higher than 1.0 and the CS, for frequencies of 1, 4, and 12 cycles per degree, was within the normal range.

The experiment was carried out with four levels of scattering: eye without filters (nonfilter), and three levels that represented different grades of cataract, obtained by means of filters BPM1, BPM2 and C3020. With the BCM, the filters were placed before the subject's eye at which the glare source was aimed, and similar measurements were made in the same conditions but without glare.

3. RESULTS

Figure 5(a) shows the values of $\log(\text{GI} + 1)$ obtained by the BCM. It should be noted that negative values of $\log(\text{GI} + 1)$ corresponded to measurements made to the nonfilter condition where the matching luminance value (Lmg) was slightly greater than the reference luminance (Lr′), showing the variability of the measurement between individuals in the psychophysical system [3]. Accordingly, Figure 5(b) shows the OSI values obtained by the DP system for all subjects and the four considered scattering conditions. While OSI values grew monotonically with the increase of scattering introduced by the filters in all subjects, the values of $\log(\text{GI} + 1)$ had a similar overall behavior, although three subjects showed some variation from this trend. In order to weigh the variability introduced by the filters against that introduced by the subjects, we performed a statistical analysis of our repeated-measures design [39], finding that the effect of the filters was much more important than the intersubject variation in the DP data (filters: $F = 97.67$, $df = 3$, and $p < 0.05$, subjects: $F = 3.54$, $df = 9$, and $p < 0.05$) as well as in the BCM data (filters:

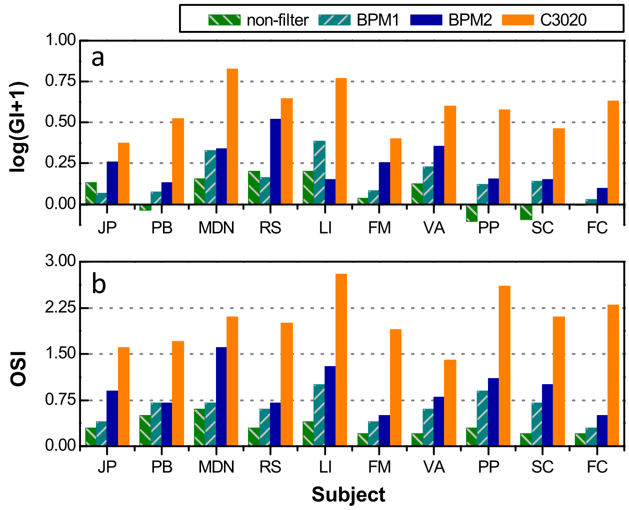

Fig. 5. (Color online) $\log(\text{GI} + 1)$ data (a) and OSI data (b) obtained for the 10 subjects and the four scattering conditions.

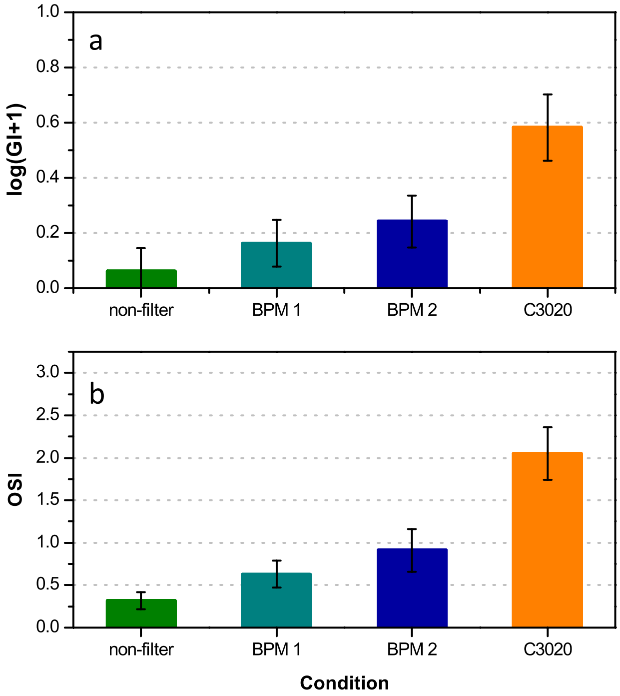

Fig. 6. (Color online) Mean values of the BCM data (a) and mean values of the data obtained by the DP system (b) in the four scattering conditions. Error bars indicate 95% confidence limits.

$df = 3$, $F = 50.09$ and $p < 0.05$, subjects $df = 9$, $F = 4.6$ and $p < 0.05$)

Therefore, the mean of $\log(\mathrm{GI} + 1)$ of all the subjects in all scattering conditions can be plotted as well as the mean of the OSI parameter (Fig. 6). The error bars correspond to the 95% confidence limits. The two measured indexes showed a graded rise with an increase of level of scattering.

To determine the significance of the differences between the values obtained for each of the conditions from the two systems, we carried out an ANOVA general linear model statistical test. As a result, at least one of the evaluated conditions was significantly different from the other conditions for $\log(\mathrm{GI} + 1)$ ($F = 27.8$, $df = 3$, $p < 0.05$) and for OSI ($F = 59.7$, $df = 3$, $p < 0.05$). In addition, Tukey's post test was used to determine whether there were differences between the conditions studied. The resulting p-values are shown in Table 2. For both $\log(\mathrm{GI} + 1)$ and the OSI, the effects assessed using C3020, BPM2 and the nonfilter conditions were significantly different, while the results obtained from the BPM1 filter could not be statistically differentiated from the nonfilter and BPM2 conditions.

Table 2. *P*-Values Obtained from the Comparison Throw Tukey Post-Test between Two Conditions for Each System[a]

Conditions Compared	$\log(GI + 1)$	OSI
C3020-Non-filter	$(T = -8,669)$ $p < 0.05$	$(T = -12,53)$ $p < 0.05$
C3020-BPM1	$(T = 6,990)$ $p < 0.05$	$(T = 10.285)$ $p < 0.05$
C3020-BPM2	$(T = 5,660)$ $p < 0.05$	$(T = 8.257)$ $p < 0.05$
Non-filter-BPM2	$(T = -3,092)$ $p < 0.05$	$(T = -4.273)$ $p < 0.05$
Non-filter-BPM1	$(T = -1,726)$ 0.33	$(T = -2.245)$ 0.13
BPM1-BPM2	$(T = 1,366)$ 0.53	$(T = 2.028)$ 0.19

[a] Between parenthesis are the T-values.

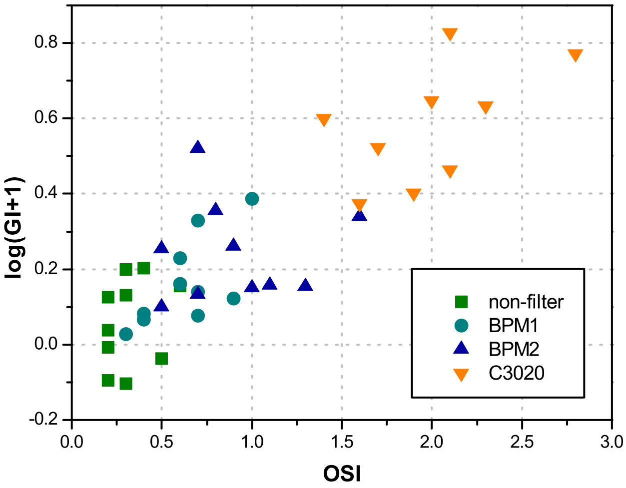

Fig. 7. (Color online) OSI values versus $\log(\mathrm{GI} + 1)$ values for all observers and the four scattering conditions.

Finally, Fig. 7 shows a scatter plot with the data collected from all subjects and for the four considered scattering conditions. In spite of the coherence of the data behavior, we could not establish a correlation between the two data sets by means of a linear fit due to the dependency among the samples [39].

4. DISCUSSION

We compared the performance of an objective system based on a DP technique and a psychophysical system based on a BCM to quantify scattering. We considered three filters characterized both by their physical properties as well as by their effects on functional vision. Figure 6 showed that $\log(\mathrm{GI} + 1)$ and OSI indexes had similar behavior assessing the same set of scattering conditions. As expected, the nonfilter condition had the least effect on the indexes; the C3020 had the highest values, while the BPM1 and the BPM2 showed intermediate effects. Although the two systems are based on different principles, both led to the same patterns of results. The conditions achieved by the BPM1 and BPM2 filters had the greatest overlap in both systems. This was expected, since the BPM2 filter only supplies slightly higher scattering than BPM1, as can be seen in their PSFs (Fig. 4) and which is also reflected in the S value (Table 1). This behavior is in agreement with previous measurements made with the same filters [12], but using a system based on the compensation comparison method [10] ($\log S = 1.30$ for BPM1 and $\log S = 1.32$ for BPM2).

According to the results of Artal *et al.* [27], an OSI below 1 corresponds to eyes with low amounts of scatter that can be considered as normal eyes, and an OSI between 1 and 3 corresponds to older eyes with associated scatter of an early cataract. The OSI values obtained with the filter BPM1 were below 1 for all subjects measured, and in the case of BPM2, the average of the OSI values were similar to BPM1, although there were three specific values above 1. In the measurements with the C3020 filter all OSI values were between 1 and 3. Considering that the two systems compared in this study showed a similar behavior, we can assert that the discriminating power of both systems allowed to distinguish normal eyes from those with low amounts of scatter, which can be associated with the subject's age or with the presence of an early cataract. This demonstrates the clinical potential of the systems evaluated. This classification does not agree with that presented in the filters section, where we showed BPM1 and BPM2 to simulate early cataracts. Different characteristics of the scattering produced by the filters and by the crystalline lens might explain this discrepancy.

The DP image is affected by both the forward and the backward scattering produced in the first and second passes of the light through the filters and the eye. Therefore the analysis of the energy distribution of DP image reveals the contribution of the light scattering, which really impairs visual performance. Although DP measurements can provide elevated values due to the light passing twice, the evaluated OSI is not intended for absolute measurements but for the relative evaluation of ocular scattering.

The fact that the effect of the three filters is similar in each of the regions of the PSF evaluated by both systems may be the reason why the two sets of results obtained in this study successfully matched. In spite of the fact that we cannot determine relationships between the PSF data of the areas that consider the DP system, it was possible to establish a qualitative coherence between the PSF/direct transmittance ratio and the OSI values determined for the three filters.

The agreement between both sets of measurements (Fig. 7) is quite good; however the correlation is not presented due to the dependency among the groups. Conversely, if only one diffusive condition is considered, poor correlation is obtained. Explanation for this lack of correlation can be performed considering some aspects of both systems. At first, the BCM is a psychophysical method that involves the optical aspects for assessment, the posterior neural processing and the response criterion. These last two aspects could insert some variability. Meanwhile, by mean of DP technique a physical measurement of the visual quality of the eye is performed. Furthermore, each system assesses different ranges of the PSF, although the relative effects between both conditions are comparable. This last aspect explains why the correlation improves if two or more scattering conditions are considered.

A more extensive study with many more subjects should be carried out to establish how the two measures correlate as a function of subject's age in the absence of any fog filters. Furthermore, new comparisons between physical and psychophysical systems would be desirable due to those will allow a mutual validation between these different approaches to measure intraocular scattering.

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