

Impact of scatter on double-pass image quality and contrast sensitivity measured with a single instrument

Juan M. Bueno, Guillermo Pérez, Antonio Benito and Pablo Artal*

Laboratorio de Óptica, Instituto Universitario de Investigación en Óptica y Nanofísica, Universidad de Murcia,
Campus de Espinardo (Edificio 34), E-30100, Murcia Spain

*pablo@um.es

Abstract: We compared objective Double-Pass (DP) image quality data with subjective visual parameters measured within the same modified instrument for different amounts of scatter. The original DP imaging channel of a clinical instrument was maintained intact and two additional channels were included, one for visual testing and another for tear film (TF) imaging by using a retro-illumination technique. Contrast sensitivity (CS) was compared with measurements of the Objective Scattering Index (OSI) obtained from DP retinal images corresponding to different scatter levels induced by pre-defined filters. OSI values were correlated with the change in CS for different spatial frequencies measured with the same instrument. Since TF and DP images were recorded at the same rate, this provided additional information about the dynamic spatial stability of the tear film. This new DP instrument has been proven to provide accuracy and repeatability, and to be suitable for clinical diagnosis, with a complete evaluation of the eye's performance by a simultaneous objective and subjective assessment under the same experimental conditions.

©2015 Optical Society of America

OCIS codes: (330.4460) Ophthalmic optics and devices; (330.7327) Visual optics, ophthalmic instrumentation.

References and links

1. J. Santamaría, P. Artal, and J. Bescós, "Determination of the point-spread function of human eyes using a hybrid optical-digital method," *J. Opt. Soc. Am. A* **4**(6), 1109–1114 (1987).
2. F. Díaz-Doutón, A. Benito, J. Pujol, M. Arjona, J. L. Güell, and P. Artal, "Comparison of the retinal image quality with a Hartmann-Shack wavefront sensor and a double-pass instrument," *Invest. Ophthalmol. Vis. Sci.* **47**(4), 1710–1716 (2006).
3. P. Artal, A. Benito, G. M. Pérez, E. Alcón, A. De Casas, J. Pujol, and J. M. Marín, "An objective scatter index based on double-pass retinal images of a point source to classify cataracts," *PLoS One* **6**(2), e16823 (2011).
4. A. Benito, G. M. Pérez, S. Mirabet, M. Vilaseca, J. Pujol, J. M. Marín, and P. Artal, "Objective optical assessment of tear-film quality dynamics in normal and mildly symptomatic dry eyes," *J. Cataract Refract. Surg.* **37**(8), 1481–1487 (2011).
5. H. Ginis, O. Sahin, A. Pennos, and P. Artal, "Compact optical integration instrument to measure intraocular straylight," *Biomed. Opt. Express* **5**(9), 3036–3041 (2014).
6. M. Vilaseca, A. Padilla, J. Pujol, J. C. Ondategui, P. Artal, and J. L. Güell, "Optical quality one month after verisyse and Veriflex phakic IOL implantation and Zeiss MEL 80 LASIK for myopia from 5.00 to 16.50 diopters," *J. Refract. Surg.* **25**(8), 689–698 (2009).
7. J. R. Jiménez, C. Ortiz, F. Pérez-Ocón, and R. Jiménez, "Optical Image Quality and Visual Performance for Patients With Keratitis," *Cornea* **28**(7), 783–788 (2009).
8. M. Vilaseca, A. Padilla, J. C. Ondategui, M. Arjona, J. L. Güell, and J. Pujol, "Effect of laser in situ keratomileusis on vision analyzed using preoperative optical quality," *J. Cataract Refract. Surg.* **36**(11), 1945–1953 (2010).
9. C. Ortiz, J. R. Jiménez, F. Pérez-Ocón, J. J. Castro, and R. González-Anera, "Retinal-Image Quality and Contrast-Sensitivity Function in Age-Related Macular Degeneration," *Curr. Eye Res.* **35**(8), 757–761 (2010).

10. M. A. Nanavaty, M. R. Stanford, R. Sharma, A. Dhital, D. J. Spalton, and J. Marshall, "Use of the double-pass technique to quantify ocular scatter in patients with uveitis: a pilot study," *Ophthalmologica* **225**(1), 61–66 (2011).
11. N. L. Himebaugh, A. R. Wright, A. Bradley, C. G. Begley, and L. N. Thibos, "Use of retroillumination to visualize optical aberrations caused by tear film break-up," *Optom. Vis. Sci.* **80**(1), 69–78 (2003).
12. H. Hofer, P. Artal, B. Singer, J. L. Aragón, and D. R. Williams, "Dynamics of the eye's wave aberration," *J. Opt. Soc. Am. A* **18**(3), 497–506 (2001).
13. A. Mira-Agudelo, L. Lundström, and P. Artal, "Temporal dynamics of ocular aberrations: monocular vs binocular vision," *Ophthalmic Physiol. Opt.* **29**(3), 256–263 (2009).

1. Introduction

The double-pass (DP) method is an objective technique based on recording images of a point-source object after reflection on the retina and a double passage through the ocular media [1]. Unlike wave-front sensors, the DP technique provides combined information of both aberrations and small-angle intraocular scatter [2]. A method to objectively measure the amount of small-angle scatter from the analysis of DP images has been used for cataract classification and for dry-eye diagnosis among others [3,4]. A modification of the DP method using an optical integration approach also allows estimating the wide-angle scatter and straylight [5].

A version of the DP device (OQAS-II, Visiometrics SL, Tarrasa, Spain) has been used in clinical environments to measure the retinal image quality under different conditions [6–10]. Although this instrument has a clear clinical potential, it cannot provide a direct correlation between the subject's visual performance and the retinal image quality estimates. Standard visual tests such as visual acuity (VA) and contrast sensitivity function (CSF) are usually measured separately.

Since objective measurements and subjective visual tests are often carried out with different instruments, a number of factors (illumination, pupil size, test distance or field of view) can limit direct comparisons and might lead to erroneous conclusions or non-accurate diagnoses. In this work, we report the modification of a commercially available DP system to include two additional channels; one for vision testing and another for tear film (TF) image acquisition by means of a retro-illumination method [11].

These modifications allow the use of a single instrument for objective and subjective measurements. Since experimental conditions are the same, direct comparison and correlations between optical image quality parameters obtained from DP images and visual function outcomes will be feasible.

2. Methods

The clinical DP instrument Optical Quality Analysis System II (OQAS II; Visiometrics S.L., Tarrasa, Spain) is designed to objectively estimate the retinal image quality of the eye from DP retinal images. The modulation transfer function (MTF) or the Strehl ratio are directly computed from DP images and used as optical quality parameters. Moreover, the Objective Scattering Index (OSI) is obtained from each DP image by comparing the light intensity in an outer ring of the DP image and that of a small circular area surrounding the image peak [3]. In the original configuration (Fig. 1, left panel), a point source image from a diode laser (DL) with a 780nm wavelength coupled to a spatial filter is projected on the subject's retina. The light coming from DL is collimated with the lens L1 and passes through an aperture, optically conjugated with the pupil of the observer and acting as the entrance pupil of the system. The beam then passes a Badal system and enters the eye. The Badal system is composed of two mirrors (M2 and M3) and two lenses (L3 and L4) and is used to compensate the spherical ametropia of the eye under study. In the second pass, a fraction of the light is reflected from the retina and after crossing the ocular media, it passes through a dichroic filter (DF), the Badal system, the mirror M1, the beam splitter BS2 and the lens L2, until it reaches the detector unit (camera CCD1). For pupil control, the eye is illuminated with a set of infrared

LEDs (IL) that does not affect the pupil's size. The corresponding reflected light is transmitted through DF and after reflection in mirror M4, it is captured by the camera CCD2. To minimize ocular movements and accommodation fluctuations during the measurement, a back-illuminated fixation test (FT) is also used. The DP instrument has been modified to incorporate a pair of additional channels. The first one was devoted to psychophysical measurements and the second one was a TF imaging channel to measure tear stability and monitor the pupil position. The fixation test in the original instrument was replaced by the visual testing channel (Fig. 1, right panel). This incorporated a micro-projector (MP) (3M Pocket Projector MPro120, 3M Projection Systems, USA) containing a liquid-crystal display operating at 800×600 resolution, with an effective pixel size of $11.75 \mu\text{m}$. The optics of the MP was substituted by a custom-made holder including a positive lens to collimate the image generated by the MP and two filters. The positive lens provided an image to the subject with enough resolution to measure the CSF (i.e. the inverse of the contrast threshold) up to 24 cycles/degree. One of the filters was a neutral density filter to increase the subject comfort when staring at the MP. The other filter was an interference filter centered at 550 nm to ensure quasi-monochromatic operation of the display. The DP image acquisition and the projection of the different stimuli on the MP were synchronized and controlled by a computer employing custom software developed in MATLAB.

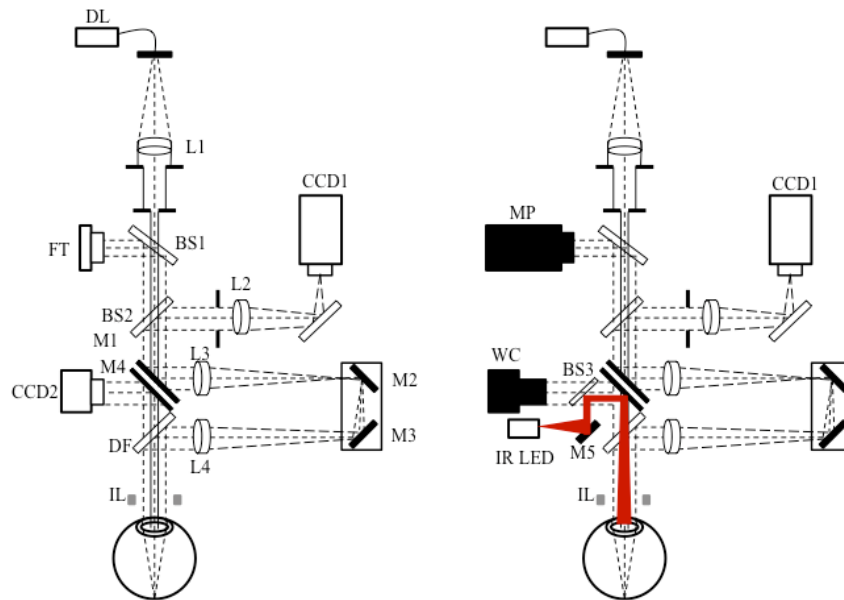


Fig. 1. Schematic diagram of the OQAS-II before (a) and after (b) the modifications reported in this work. DL, diode laser; FT, fixation test; L1-L4, lenses; M1-M5, mirrors; BS1-BS3, beam splitters; CCD1-2, cameras; DF, dichroic filter; IL, infrared LEDs; WC, Webcam; MP, microprojector.

In the new channel for TF imaging, the camera (CCD2) originally used for pupil alignment was replaced by a Webcam (WC, VGA sensor 1.3Mpixels). An infrared fiber-coupled LED (IR LD, 850 nm wavelength), a mirror (M5) and a beam splitter (BS3) were also incorporated to illuminate the anterior part of the eye. This channel will be used to monitor dynamic changes in the TF. Custom software also allowed the simultaneous recording of TF and DP images at predefined time intervals (here at 2 Hz). The results obtained from this specific application for tear film quality are out of the scope of the present manuscript, and they will be presented in a separate work. The rest of elements of the original configuration were not modified and the DP channel was then completely operative.

All DP images were acquired for a 4-mm pupil at the best focus. The spherical refractive error (defocus) of the subjects was corrected by the instrument with the Badal optometer. When necessary, astigmatism was corrected by using cylindrical trial lenses placed in front of the eye. As an example, two DP and TF images simultaneously acquired with the modified instrument are shown in Fig. 2.

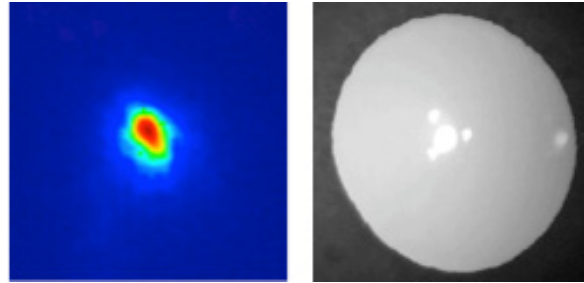


Fig. 2. Example of a DP (left) and TF (right) images recorded with the modified OQAS-II instrument.

After the changes in the OQAS-II were made, an initial validation test was performed to assure that the OSI values were kept constant. Then additional tests involving OSI and CSF measurements for different experimental conditions were performed. Three well-trained healthy subjects were involved in the study (the right eye of each subject was used): #1 (male, 49 y/o), #2 (female, 27 y/o) and #3 (male, 24 y/o). The study followed the tenets of the Declaration of Helsinki, and signed informed consent was obtained from the subjects after the nature and all possible consequences of the study had been explained. For each subject the CSF was estimated at spatial frequencies of 6, 12, 18 and 24 cycles/degree. Changes in contrast, set at steps of 1%, were controlled by the subject using an independent keyboard. For each pre-defined spatial frequency the subjects were first asked to increase the contrast of the grating until it could be clearly seen. Then they proceed to slowly reduce the contrast until it was not perceived. Finally they were asked to increase the contrast until they were again able to perceive the grating. This contrast value was set as the threshold for each particular spatial frequency. CS values were compared with the OSI values computed from the corresponding DP images. For all subjects both DP image recording and CSF measurement were performed under the following five experimental situations. The control condition measured the eyes without filters. The rest of experimental conditions involved the use of four different diffusers (scattering filters) in front of the eye. Filters #1 and #2 were silicon-made filters (the thickness of #2 was twice that of #1). Filter #3 was composed of microspheres over a glass slide, and filter #4 was a holographic-type. All measured parameters were the average result computed from at least three consecutive measurements.

3. Results

Figure 3 shows the OSI (averaged for the three subjects) as a function of increasing added defocus (ranging from 0.0 to 2.0 D), before and after modifying the OQAS-II. It can be noted that OSI values hardly changed after the two additional channels in the instrument were included. This can be expected since the optical channels of DP measurements remained unaltered. Moreover, it is worth to note that OSI values were larger than 1.0 for uncorrected defocus values over 1.0 D. This indicates that refractive error must be corrected at least with a precision better than 1.0 D of spherical equivalent before DP images are acquired for proper OSI estimations, as previously reported [3]. This initial validation test leads to assume that DP measurements were not affected by changes performed on the OQAS-II.

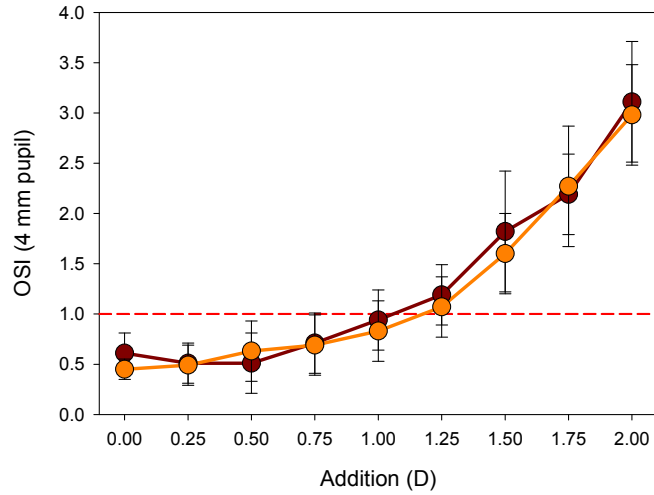


Fig. 3. Comparison of averaged OSI values for all subjects as a function of defocus before (dark red) and after (orange) modifying the OQAS-II. The dashed line corresponds to the limit of a nominal normal OSI value. Error bars represent the standard deviations.

In the following, the relationship between the ocular scatter and the related visual outcomes will be explored with the modified instrument. Figure 4 depicts the OSI values for all eyes and induced scatter levels. For completeness, two DP images (insets) are also shown for the conditions indicated. As expected OSI values increased with the amount of scatter introduced by the filter placed in front of the eye. Without filter the value was similar in all subjects (~ 0.5) while with filter 4 OSI ranged between ~ 4 (subject #2) and ~ 9 (subject #1).

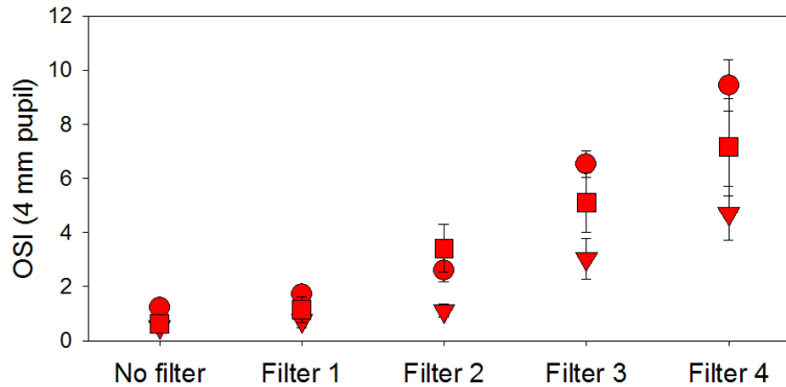


Fig. 4. Average OSI values for all subjects (#1, circles; #2, triangles; #3, squares) obtained from DP images acquired with the eye alone and using the four scatter filters. Error bars correspond to the standard deviation computed from three DP images.

For each subject and scatter filter, DP images were recorded and CSF measurements were carried out. As an example, Fig. 5 presents the results of CSF for all scatter filters in subject #2. It can be observed that the CS decreased with increasing scatter for each spatial frequency. For a better understanding of the effect of scatter on visual performance, for each scatter filter and spatial frequency an impact factor parameter was computed as:

$$\text{Impact factor} = 1 - \left(\frac{CS_{\text{eye+filter}}}{CS_{\text{eye}}} \right).$$

Whereas a null value means no effect of the scatter on the CS for that particular spatial frequency, a value close to 1 means a large decrease in the CS for that frequency. Figure 6 shows the corresponding results. Overall, the impact factor increased with scatter for each spatial frequency, although at 6 c/deg filters 1 and 2 provided similar results (and also filters 3 and 4 at 18 c/deg). For each subject and scatter-induced condition the best linear fit of the corresponding CSF was computed (see also Fig. 5). This linear regression allowed us to obtain the cut-off frequencies corresponding to high-contrast (HC, when the CSF reached a sensitivity of 1), and low-contrast (LC, when the CSF was 10). The results for one of the subjects are presented in Fig. 7.

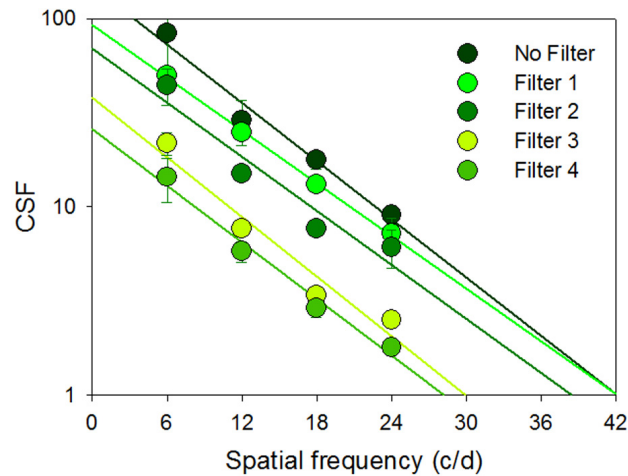


Fig. 5. Average CS (in log scale) at four different spatial frequencies for subject #2 and all scatter filters. Lines correspond to the best linear fitting. Error bars represent standard deviation (some are within the symbols).

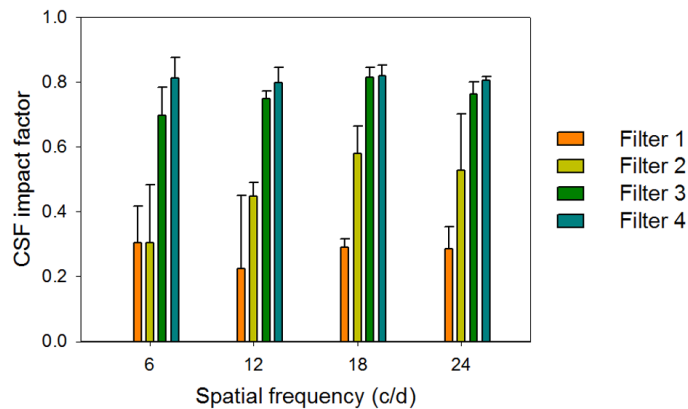


Fig. 6. Average impact factor on the CS when using the different scatter filters. Error bars represent the standard deviations across subjects.

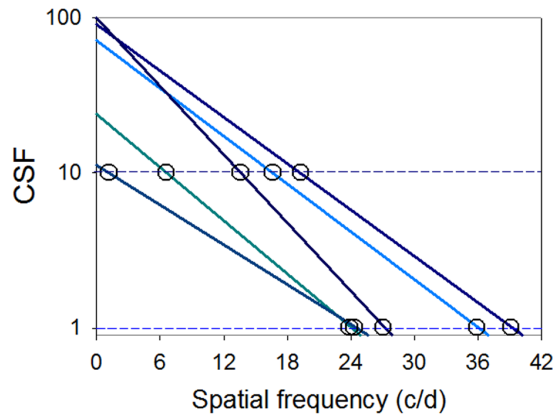


Fig. 7. Cut-off frequencies (circles) for HC and LC computed from the linear fits to the real CSF data. Data correspond to subject #1. Labels are the same as in Fig. 5.

To further explore the impact of scatter on visual outcomes, the HCVA and the LCVA (white circles) were calculated as a function of the OSI values. Results for the three subjects, five experimental conditions and expressed in standard logMAR scale are depicted in Fig. 8. The increase in scatter moderately reduced the HCVA: an increase in one unit over the OSI scale led to an increase of HCVA of 0.031 logMAR ($R^2 = 0.75$). However, the impact of increasing scatter was significantly larger on LCVA values: one unit of OSI represents an increase of 0.127 logMAR ($R^2 = 0.93$). Scatter has a relatively minor effect on the HCVA (Fig. 8). However visual performance measured through the CS is significantly affected. Figure 9 shows the CS values obtained at 12 cycles/deg as a function of the OSI values for all subjects. The experimental CS data showed an exponential decay with increasing OSI, following the relation: $CS_{12\text{ c/d}} = 27.2 \cdot e^{(-0.31 \cdot OSI)}$ ($R^2 = 0.81$).

All results presented have combined the CSF measurements obtained using the new visual testing channel and the OSI values computed from “static” DP image acquisition. However, for the sense of completeness and in order to show an example of the ocular temporal evolution, Fig. 10 depicts two DP images together with the companion TF images (recorded using the new TF imaging channel) in one of the subjects. Consecutive pairs of TF-DP images were recorded every 0.5 seconds. At the starting point of the DP images sequence (0 seconds) the patient was told to blink twice and then kept the eye open. The initial TF-DP image pair (left) represents a normal TF condition. After about 15 seconds of blinking absence a high degradation of the DP images can be observed. The corresponding TF image also shows the non-uniformity distribution of the tear-film when breakage took place.

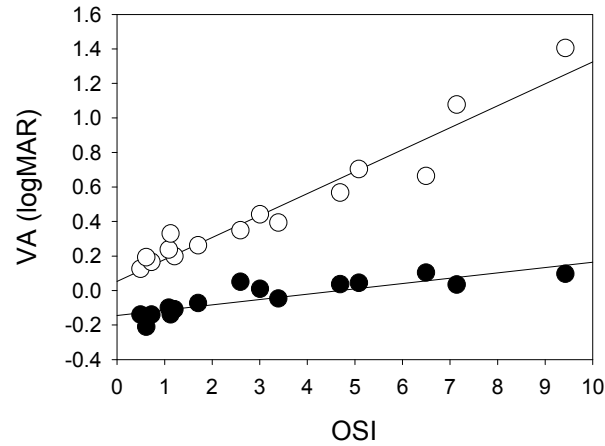


Fig. 8. HCVA (black symbols) and LCVA (white symbols) estimates for all subjects and experimental conditions as a function of OSI values.

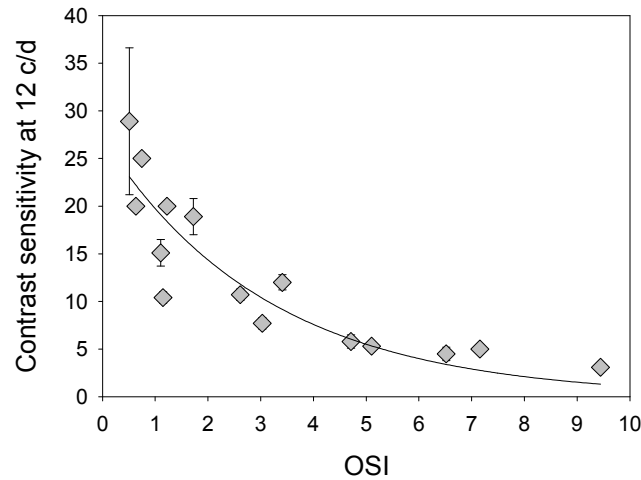


Fig. 9. CS values at 12 c/deg for all subjects and experimental conditions versus OSI values. Error bars represent standard deviations.

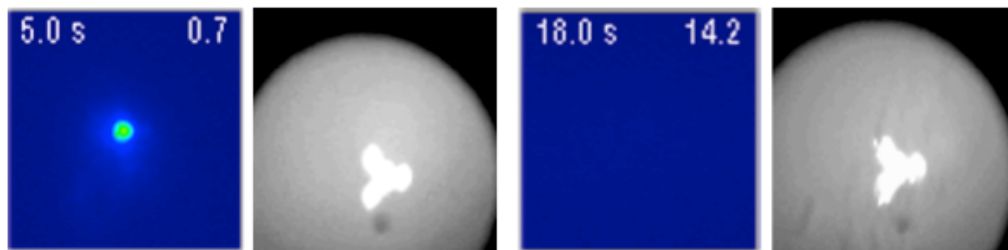


Fig. 10. DP and TF images of a normal eye acquired at two different time points. The numbers on DP image indicate the time after blinking (left corner) and OSI value (right corner).

4. Discussion

We have reported a modified clinical DP instrument to combine objective and subjective visual testing measurements. For this aim, two extra channels were included in an OQAS II, one for visual testing and another for TF image recording. Although different optical elements

were added to the original configuration, the original DP channel kept intact. The experimental system was completely controlled by custom software. Image recording (both DP and TF) were synchronized with the stimulus projection on the MP. The biggest advantage of this version of the DP instrument is the combination of objective measurements and subjective visual testing in a unique platform. In the regular clinical practice, they are carried out using different instruments and it is complex to establish reliable relationships between the retinal image quality and the visual function outcomes. The combination here reported overpasses these limitations and allows not only a direct comparison for each subject, but also a more in-depth analysis of the visual performance for different experimental conditions. To our knowledge, instruments with these characteristics have not previously been reported. These objective-subjective comparisons might be very useful in the diagnosis and following-up of certain ocular pathologies (keratitis, macular degeneration...) where a decrease in retinal image quality is strongly associated with a reduction in the subject's visual performance. The new configuration of the clinical instrument enhances its functionalities and it is directly suitable for clinical environments. Particular attention was paid to the measurements of the OSI parameter under different conditions and its effects on visual performance (evaluated by means of the CSF). As expected, the CSF decreased with the increase of scattering for different spatial frequencies (Figs. 5 and 6). In addition, that information allowed the calculation of both HCVA and LCVA. Whereas scatter was shown to have little impact on the former, the latter strongly depend on it (Fig. 8). The provided relationships between the optical and visual parameters could be of interest for protocols to detect normal optical or neural visual deficits. Another interesting aspect of the reported instrument is the possibility of dynamic analyses. Despite the fact that the eye is not a static optical system, its dynamic behavior is often forgotten [12,13]. After the modifications, the experimental device included a channel developed for dynamic TF imaging. Successive and simultaneous DP and TF images can be acquired at predefined time intervals (Fig. 10). At the same time, visual tests can also be performed. This dynamic use of the instrument is essential to perform reliable and accurate tests in patients suffering from tear deficiencies, as could be dry-eye syndrome, where TF and DP images noticeable deteriorate and the visual function is clearly affected within short-term temporal intervals. This offers a new tool to perform dynamic measurements of ocular image quality and the possibility of combining them with subjective tests using a unique instrument.

In summary, a commercial clinical instrument has been modified to combine, in a unique platform, objective measurements of the optical quality of the eye (by means of the MTF and/or the OSI) and subjective visual testing functions. The combinations of objective retinal quality estimates with psychophysical measurements, such as CS or LCVA, can be useful for a better understanding of the visual performance.

Acknowledgments

This research has been supported by the European Research Council Advanced Grant ERC-2013-AdG-339228 (SEECAT) and the Spanish SEIDI, grant FIS2013-41237-R. One of the authors (PA) has a financial interest in Visiometrics SL, manufacturer of OQAS-II.