Comparison of the Retinal Image Quality with a Hartmann-Shack Wavefront Sensor and a Double-Pass Instrument

Fernando Díaz-Doutón,[1] *Antonio Benito,*[2] *Jaume Pujol,*[1] *Montserrat Arjona,*[1] *José Luis Güell,*[3] *and Pablo Artal*[2]

Purpose. Wavefront sensors provide quite useful information on the optical quality of the eye. However, in eyes where very high-order aberrations and scattered light are prominent, wavefront sensors may overestimate retinal image quality. This study showed that, in those cases, the double-pass technique is a complementary tool for better estimation of ocular optical quality.

Methods. A double-pass (DP) instrument was used, based on recording images of a point source in near-infrared light after reflection in the retina and double-pass through the ocular media. The aberrations were also measured with a prototype of near-infrared Hartmann-Shack (HS) wavefront sensor adapted to the clinical environment. From the wave aberrations, the modulation transfer function (MTF) was calculated (MTF_HS). The MTF was also obtained from the double-pass images (MTF_DP). Both techniques were applied in normal young subjects as the control and in three other groups of eyes: older subjects, after LASIK refractive surgery, and after IOL implantation.

Results. The MTFs obtained from DP and HS techniques were compared. In the group of normal eyes with low levels of intraocular scattering, these estimates were quite similar, indicating that both techniques captured well most of the optical degradation. However, in eyes where scatter was more predominant (e.g., early cataract, posterior capsular opacification after IOL implantation) the MTF provided by the HS sensor was always higher than the MTF obtained from DP. A single parameter was used to indicate the differences.

Conclusions. In eyes with low scattering, DP and HS techniques provided similar estimates of the retinal image quality. However, in a patient's eye with mild to severe amount of scatter, wavefront sensors might overestimate image quality, whereas the DP technique produces a more accurate description of the optical quality, better correlated with the quality of vision. (*Invest Ophthalmol Vis Sci.* 2006;47:1710–1716) DOI: 10.1167/iovs.05-1049

From the [1]Centre de Desenvolupament de Sensors, Instrumentació i Sistemes, Universidad Politécnica de Cataluña, Terrassa, Spain; the [2]Laboratorio de Óptica, Departamento de Física, Universidad de Murcia, Murcia, Spain; and the [3]Instituto de Microcirugía Ocular (IMO) and Universidad Autónoma de Barcelona (UAB), Barcelona, Spain.

Supported by Ministerio de Educación y Ciencia Grants BFM2001-0391 and FIS2004-2153 (PA) and DPI2002-0118 (JP).

Submitted for publication August 9, 2005; revised October 2 and December 13, 2005; accepted February 16, 2006.

Disclosure: **F. Díaz-Doutón**, None; **A. Benito**, None; **J. Pujol**, Visiometrics, SL (I, C, P); **M. Arjona**, Visiometrics, SL (I, C); **J.L. Güell**, Visiometrics, SL (I, C); **P. Artal**, Visiometrics, SL (I, C)

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked "*advertisement*" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: Pablo Artal, Laboratorio de Optica (Departamento de Física), Universidad de Murcia, Campus de Espinardo (Edificio C); 30071 Murcia, Spain; pablo@um.es.

The recent advances in methods to measure the ocular wavefront aberration have provided very useful information about the eye's optical performance in monochromatic light. The number of studied eyes has dramatically increased in the past years, helping the analysis of aberration structure both in the normal population[1–3] and in eyes affected by different types of diseases or after ocular surgery.[4] The relative contribution of cornea and lens to the complete eye has also been reported by combining total and corneal aberrations.[5,6] In contrast, the double-pass (DP) technique, was proposed to estimate the retinal image quality half a century ago.[7] The technique is based in the recording of the retinal image after double-pass through the ocular media and retinal reflection. The method incorporated different technical innovations[8–10] and demonstrated to provide accurate estimates of the eye's image quality. From the double-pass images, the ocular modulation transfer function (MTF) is determined. The MTF provides information on the overall optical performance of the human eye, including all the optical defects involved in retinal image degradation, such as diffraction, aberrations, and scattering. This property of the DP method of capturing all the relevant information affecting the retinal image renders the approach extremely powerful in many of the conditions that specially affect scattering. In particular, the method has been used to investigate retinal image quality as a function of age,[11,12] after the use of contact lenses,[13] or after implantation of intraocular lenses.[14,15]

Despite the potential of the DP technique, in the past decade, most of the attention has been directed to the measurements of the ocular aberrations by using wavefront sensors. These sensors are being used in clinical ophthalmology (mostly in refractive surgery) and also in vision research, where the correction or manipulations of the eye's aberrations (adaptive optics[16,17]) was used in different experiments.[18,19] Although a large number of different techniques have been developed for measuring the eye's aberrations (e.g., the crossed-cylinder aberroscope,[20] the spatially resolved refractometer,[21] the laser ray-tracing method,[22] phase-retrieval from DP images,[23] and the pyramidal sensor[24]), the Hartmann-Shack (HS) sensor[25–27] is the most commonly used today, and the base for most of the clinical devices currently available. Although, the wavefront sensors are extremely useful, their main drawback is the lack of information on quite higher-order aberrations and scattering, due to limitation imposed by lens sampling.

Intraocular scattering[28] affects the image quality, reducing quality of vision. In normal, young, healthy eyes its impact is usually small for most visual tasks, but that is not the case in other subjects with ocular conditions such as cataract, older eyes, or refractive surgery. Several methods have been proposed to estimate scatter, including psychophysical techniques,[29] and others based in Scheimpflug imaging, dynamic light scattering,[30] or the analysis of Hartmann-Shack images.[31] However, there is still a lack of robust objective techniques to measure scatter. Moreover, although scatter may affect wave-

Investigative Ophthalmology & Visual Science, April 2006, Vol. 47, No. 4

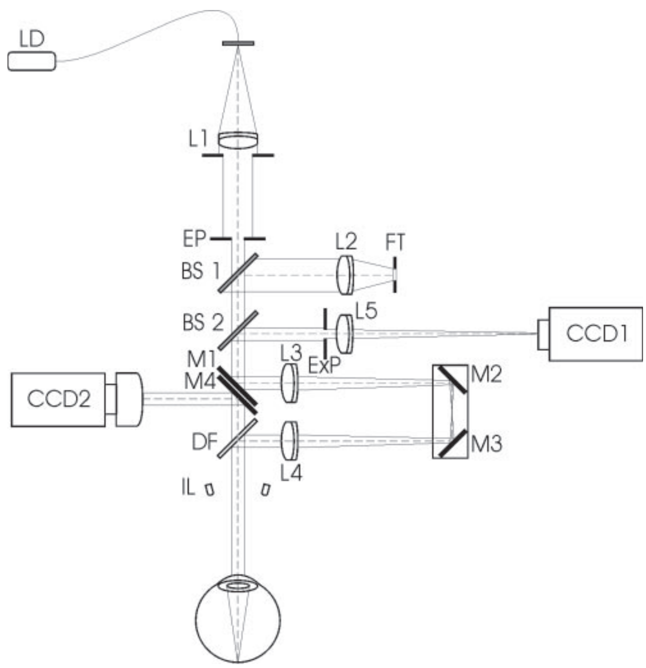

FIGURE 1. The DP experimental setup.

front sensors, in general, these devices are not designed to capture this information. On the contrary, the DP method carries the complete information on the retinal image.

In this context, the main purpose of the present study was to compare the results obtained when both techniques, DP and HS, were applied under comparable conditions in different subjects: normal older subjects after standard refractive surgery and IOL implantation, compared with a control group of normal young subjects. This comparison will be of help to know whether wavefront sensors overestimate retinal image quality in some cases. In addition, it will show the that intraocular scattering in different eyes can be used as a means of characterizing image quality more in relation to quality of vision. This research has been reported in part in abstract form (Pujol J, et al. IOVS 2003;44:ARVO E-Abstract 2546).

METHODS

DP Instrument

The DP measurements were performed with a commercially available instrument (Optical Quality Analysis System [OQAS], Visiometrics SL, Tarrasa, Spain). Figure 1 shows a schematic diagram of the apparatus. It corresponds to an asymmetric double-pass configuration,[32] allowing the capture of the possible asymmetries in the retinal images otherwise lost in the conventional DP system (see Ref. 33 for further discussion on the image-forming properties in the DP). A point source is projected on the retina. After retinal reflection and DP through the ocular media, a camera records the DP image. The entrance pupil (EP) has a fixed diameter of 2 mm, whereas the exit pupil (ExP) is controlled by a diaphragm wheel, ranging from 2 to 7 mm. As a point source, an infrared laser diode (LD; λ = 780 nm) coupled to an optical fiber is used. For the subject's defocus correction, a motorized optometer, consisting of two lenses (L3, L4) with a 100-mm focal length and two mirrors (M2, M3), is used to correct defocus. An infrared video camera (CCD1), with a pixel size of 8.4 μm, records the DP images after the light is reflected in the retina and beam splitter (BS2). Pupil alignment is controlled with an additional camera (CCD2). A fixation test (FT) helps the subjects during the measurements. Additional technical details on this instrument are described elsewhere.[34] We used near-infrared light to record the DP images. This method was more comfortable for the subject, and, in addition, it has been shown that it provides adequate estimates of the retinal image quality compared with those obtained with visible light.[35]

HS Instrument

The wavefront aberration measurements were performed using our custom-made research prototype HS wavefront sensor, adapted for the clinical environment. This system, described elsewhere,[27] consists of a microlens array (ML), conjugated with the eye's pupil, and a camera placed at its focal plane. If a plane wavefront reaches the microlens array, the camera records a perfectly regular mosaic of spots. However, if a distorted (i.e., aberrated) wavefront reaches the sensor, the pattern of spots is irregular. The displacement of each spot is proportional to the derivative of the wavefront over each microlens area. From the images of the spots, the wavefront aberration was computed and expressed as a Zernike polynomial expansion.[36] The light source was also a near-infrared laser diode (λ=780 nm) and the microlens array had an effective aperture size of 0.3 mm at the entrance pupil plane. The accuracy and precision of the system was assessed previously to the data collection in subjects by using controlled defocus and calibrated spherical aberration plates. The precision of the HS system measuring defocus was better than 5% in all cases. A schematic diagram of the apparatus is shown in Figure 2.

Subjects

Twenty eyes were investigated and included in one of the following groups: (1) control group of normal young eyes (n = 7) aged 39.4 ± 3.1 years; (2) normal old subjects (n = 6) aged 69.0 ± 9.7 years (in some cases with cataract in its very early stages); (3) pseudophakic eyes, after successful IOL implantation (n = 4), aged 44.5 ± 26.4 years; and (4) subjects after standard LASIK refractive surgery (n = 3), aged 27.3 ± 5.8 years. All clinical examinations, surgeries and measurements were conducted at the IMO, Barcelona (Spain). Practices and research adhered to the tenets of the Declaration of Helsinki. Informed consent was obtained from the subjects after explanation of the nature and possible consequences of the procedures. The study was approved by the ethics committee for clinical investigation at IMO-UAB.

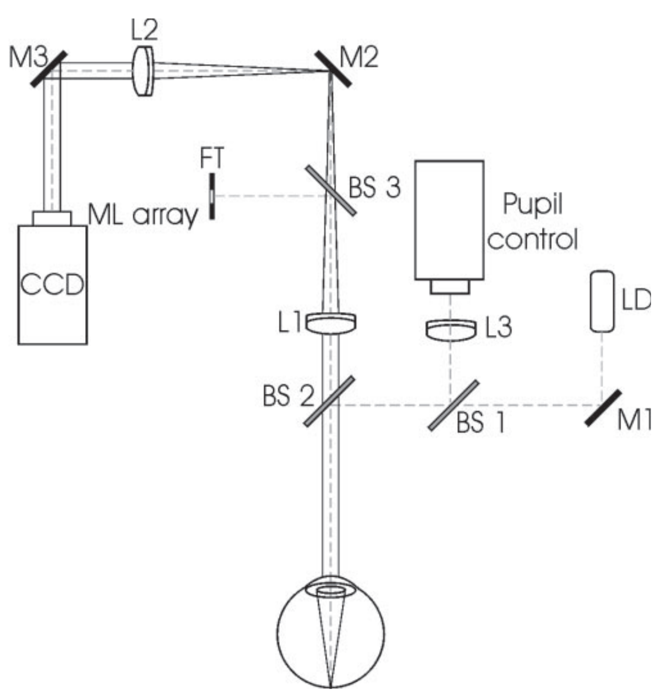

FIGURE 2. The HS wavefront sensor.

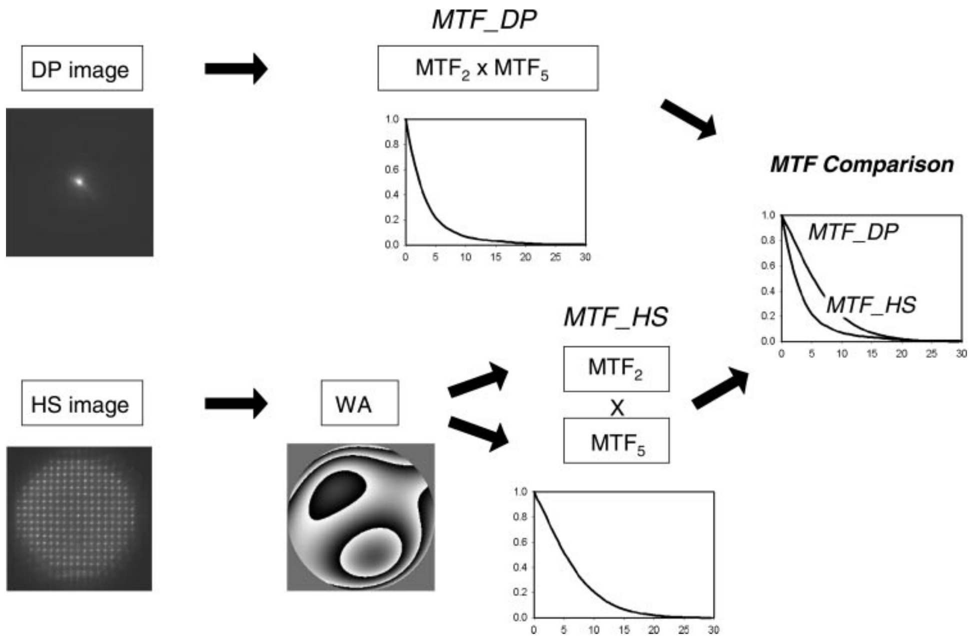

Figure 3. The procedure for comparison of the DP and HS methods.

Experimental Procedure

Both DP and HS measurements were performed under natural viewing conditions, with a fixation test placed at infinity. A dim ambient light was maintained in the room to assure at least a 5-mm natural pupil diameter. For each eye, 20 DP images were recorded for both symmetric configuration (entrance and exit pupil of 2 mm) and asymmetric configuration (entrance pupil, 2 mm; exit pupil, 5 mm). In both cases, possible refractive errors were corrected by using the motorized optometer. Five HS images were recorded, processing the ocular wavefront aberration for the whole available pupil, using a Zernike polynomial expansion up to the sixth order. For comparison with the DP measurements, the wave aberrations were recalculated for the selected pupil diameters (2 or 5 mm), centered at the geometric center of the pupil. The complete set of DP and HS measurements lasts approximately 5 minutes and is comfortable for the subjects.

Theory

We used the MTF as the reference for the comparison of the retinal image quality provided by the two methods. MTF represents the loss of contrast produced by the eye's optics on a sinusoidal grating as a function of its spatial frequency. The MTFs were computed from both the HS and DP images to be compared. Figure 3 presents a schematic diagram of the procedure. The Fourier transform of the DP image captured with aperture diameter 2 and 5 mm corresponds to the product of the MTFs for such pupil diameters ($MTF_2 \times MTF_5$).[33] In contrast, from the HS image, the MTF is easily computed[27] independently for each pupil diameter (MTF_2 and MTF_5). The product of the two MTFs will be used to compare both methods. Because two different instruments were used, the possible differences in defocus could be a source of discrepancy. We minimized this problem by using the following approach. DP images were collected at the best focus position. A series of images was first recorded at 0.1-D intervals and the best focus position selected. From the HS data, we chose the value of defocus that maximized image quality (i.e., producing the maximum Strehl ratio (SR)). Beyond the direct comparison of MTFs provided by both methods, we also used the SR as a single metric to compare the estimates of image quality provided by both methods. The SR is a parameter commonly used for estimating the overall optical quality, defined as the ratio of the intensity at the peak of the image formed by

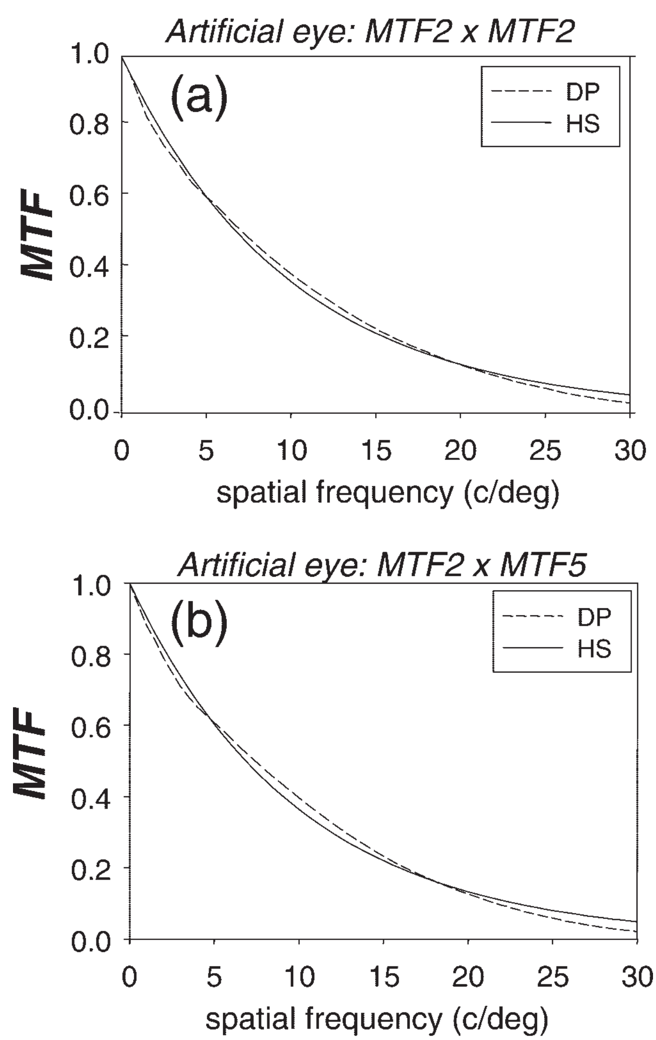

Figure 4. Comparison of MTFs obtained with the two methods in an artificial eye: HS (*solid line*) and DP (*dotted line*); (**a**) 2-mm EP and ExP; (**b**) 2-mm EP and 5-mm ExP.

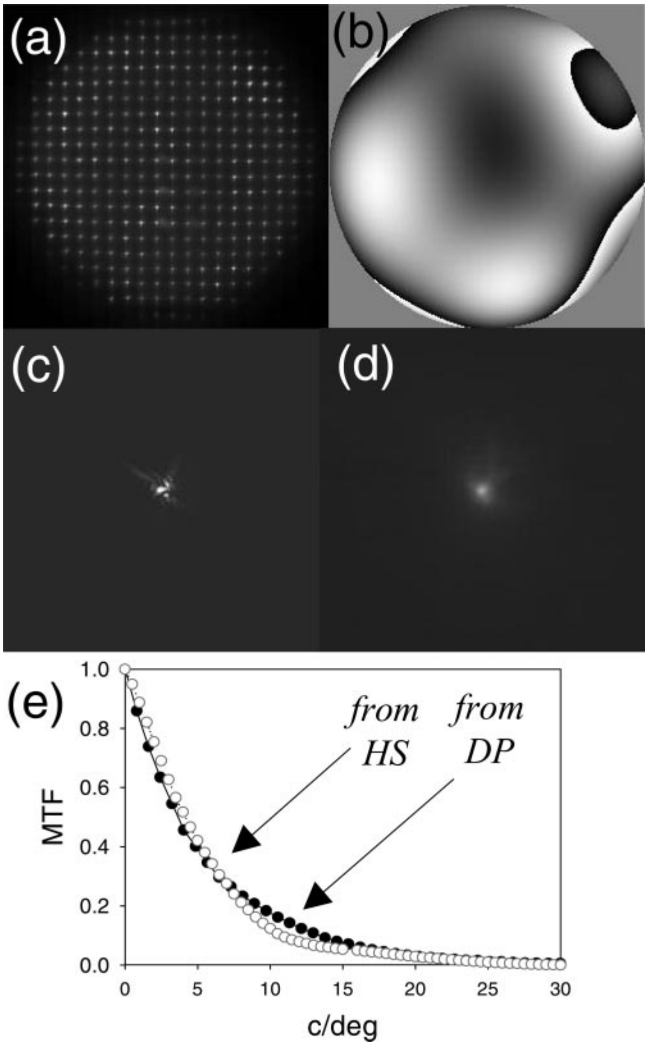

FIGURE 5. Example of results in an eye from the normal young group. (**a**) HS image; (**b**) reconstructed wave-aberration; (**c**) DP retinal image computed from the wave aberration; (**d**) DP retinal image directly recorded with the DP instrument; and (**e**) MTFs from HS and DP.

an aberrated optical system to the intensity of the an aberration-free system. A fraction of SR provided by the two methods was calculated:

$$SR_{HS\text{-}DP} = \frac{SR_{HS} - SR_{DP}}{SR_{HS}} \quad (1)$$

This parameter, $SR_{HS\text{-}DP}$, accounts for the difference between both DP and HS. The MTF calculated from HS (MTF_HS) provides information on aberrations (up to midorder, depending on the reconstruction and the area of the microlens). In contrast, the MTF obtained from the DP images (MTF_DP) provided all the information affecting the retinal image quality, including aberrations (up to a very high order) and scattered light. A small or zero value of the parameter accounts for an eye where both methods provide similar performance (i.e., where high order and scatter make a minor contribution). A positive value means that the image quality estimated with the HS is better than with the DP. This indicates that the eye has a significant component of high-order aberrations and scatter (not captured by the HS). We also estimated the relative contribution of high-order aberration and scatter as a function of the spatial frequency (f) by calculating ($S(f)$):

$$S(f) = [MTF_{HS}(f)/MTF_{DP}(f)] - 1 \quad (2)$$

Calibration of the Instruments

Before performing the experiment in the subjects, we compared the instrument and the complete procedure in an artificial eye. This system is mainly affected by aberrations, with an expected minor effect of scattered light. Under this assumption, the MTFs obtained by the two methods should be similar. The results of two pupil configurations (2 mm) and (2 and 5 mm) are presented in Figure 4. In both cases, MTFs were very similar. The small differences may be due to slight differences in centration in both instruments. This result further validates the performance of both techniques under controlled conditions and the validity of the comparisons.

RESULTS

We first collected data in the control group of normal young subjects. Figure 5 shows as an example of results for one of the subjects. The HS image (Fig. 5a), the reconstructed wavefront (Fig. 5b) and the calculated DP image (Fig. 5c; from the HS data). This image should be compared with the DP image directly recorded (Fig. 5d). The MTFs from both techniques are also compared (Fig. 5e). As expected, since scatter and very high-order aberrations should have a small contribution in this subject's eyes, both methods provide similar estimates of image quality. Figure 6 shows the average MTFs in all subjects in this group. Although the MTFs obtained by both HS and DP were similar, we found a slightly lower MTF for the DP measurements. This could be explained by the slightly different focus setting in both techniques.

A very different situation occurred when the procedure was applied to an older eye with early cataract. In this case, scatter severely affected the retinal images, but the aberrations were normal values. Figure 7 shows the set of results for this subject: the HS image (Fig. 7a), the reconstructed wavefront (Fig. 7b); the calculated DP image from the HS data (Fig. 7c) and the DP image directly recorded (Fig. 7d). The MTFs from both techniques are also compared (Fig. 7e). It should be noted that in this case (early cataract) it was still possible to record the HS image and then calculate the associated aberrations. In this subject, the DP retinal image is clearly more extended than that associated only to the aberrations (estimated from the HS). In addition, the MTFs showed an important difference, with the MTF for HS overestimating the retinal image quality.

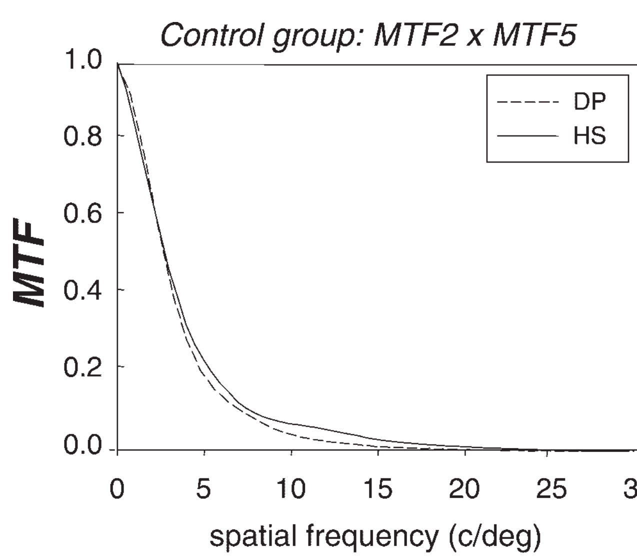

FIGURE 6. MTFs (product of MTFs for 2 and 5 mm) averaged for all subjects in the control group: HS (*solid line*) and DP (*dashed line*).

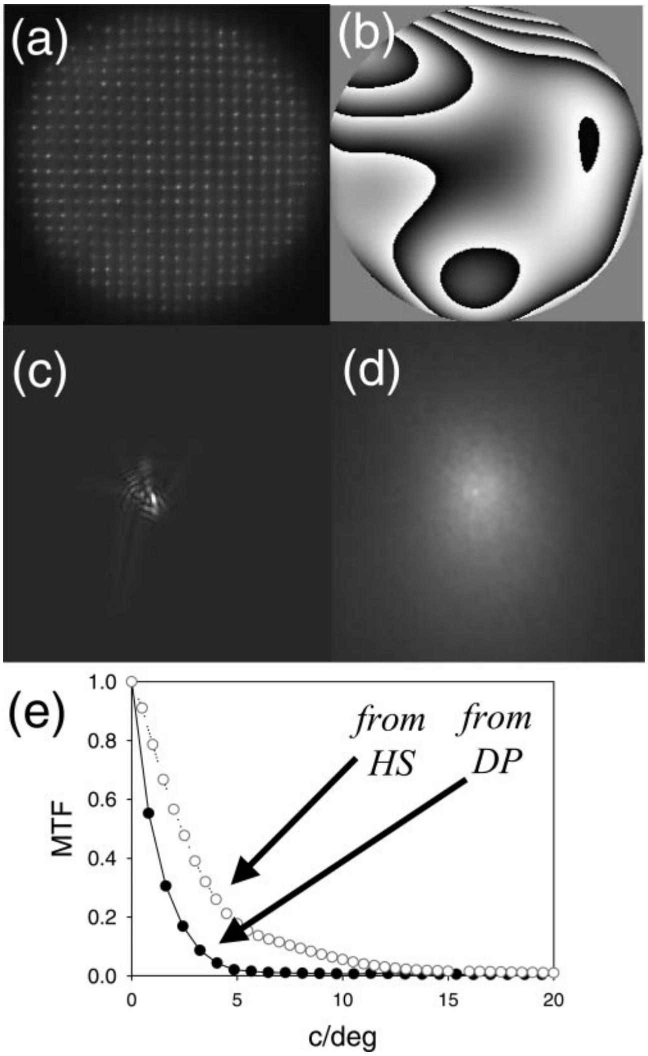

FIGURE 7. Example of results in an eye from the older group (with an early stage of cataract). (**a**) HS image; (**b**) reconstructed wave-aberration; (**c**) DP retinal image computed from the wave aberration; (**d**) DP retinal image directly recorded with the DP instrument; and (**e**) MTFs from HS and DP.

Figure 8 shows the average MTF results for the other three groups of subjects: (Fig. 8a) older subjects (some with early cataract; Fig. 8a); eyes that underwent standard LASIK refractive surgery (Fig. 8b); and eyes after IOL implantation (some with minor capsular opacification; Fig. 8c). In all the three groups, the MTFs estimated from the HS are higher than from the DP. This indicates the important contribution of scatter in these eyes. The larger difference was obtained in the group of older subjects, where some cases presented early stages of cataract development, leading to a significant increment of scatter. The group of post-LASIK subjects, although they were even younger that the control group, showed a higher MTF from HS than from DP, perhaps due to an increment in the very high-order aberrations and/or surgically induced corneal haze. The last group, corresponding to patients with IOLs, showed similar differences, in this case probably because of the presence of some posterior capsular opacification.

Figure 9 shows for the average for each group of the function $S(f)$ (equation 2) calculated for 2- and 5-mm pupil diameters. This is a direct comparison of the MTFs obtained from HS and DP, for spatial frequencies up to 30 cyc/deg. Using equation 1, we also calculated $SR_{HS\text{-}DP}$ for all the subjects, and compared the mean within groups (Table 1). This is a single parameter that indicates the relative effect of scatter or extremely high-order aberrations. A higher value of the parameter indicates a larger impact of these factors. For both the 2- and 5-mm pupil size, the group with older subjects showed the largest value, indicating more light diffusion (it should be noted than in this group, some eyes presented early stages of cataract development). In post-LASIK and IOL eyes, the parameter was lower than in group 2, but still clearly higher than in the control group of young healthy eyes.

In a number of eyes, visual acuity data collected clinically were available. Figure 10 shows for this smaller subgroup of seven eyes, how the optical parameters obtained by the two methods were related to visual acuity. The parameters SR_{HS} and SR_{DP} were similar in the eyes with higher acuity, but in the cases of eyes with more scattered light, SR_{DP} provided a better prediction of acuity. The DP-based parameter is well fitted with a linear function to the acuity (Fig. 10, dashed line), whereas the HS parameter is fitted with a quadratic function (Fig. 10, solid line). Although this is a good indication that the DP estimates are better correlated with visual quality, since we

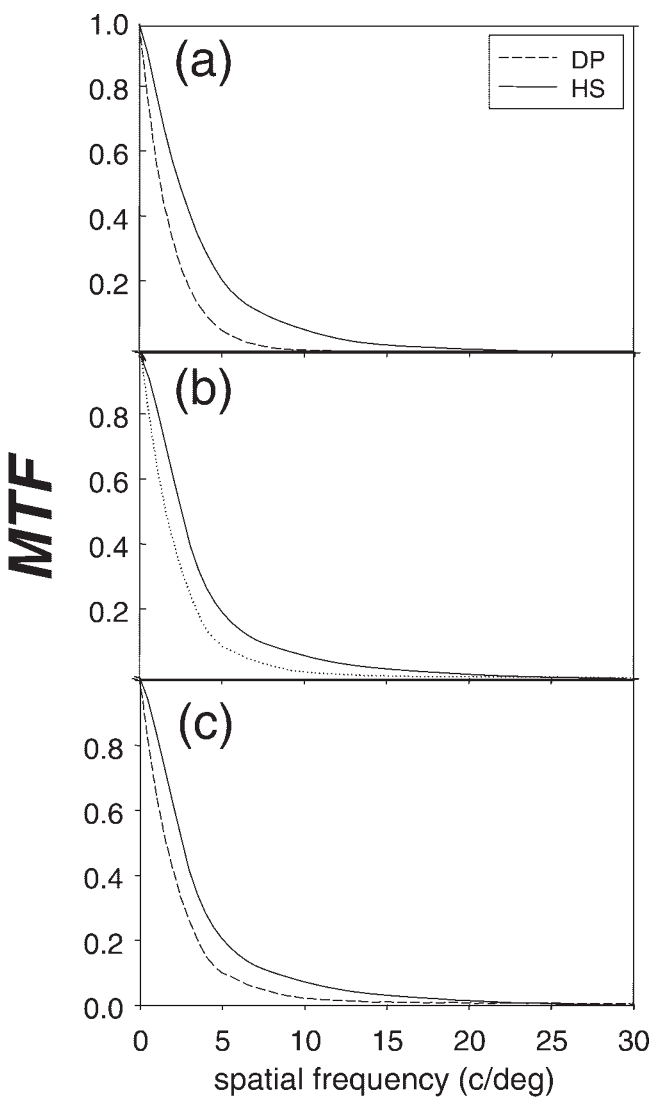

FIGURE 8. MTFs (product of MTFs for 2 and 5 mm) averaged for all subjects in the older subject group (**a**); the eyes after post-LASIK refractive surgery (**b**) and after IOL implantation. (**c**). HS (*solid line*) and DP (*dashed line*).

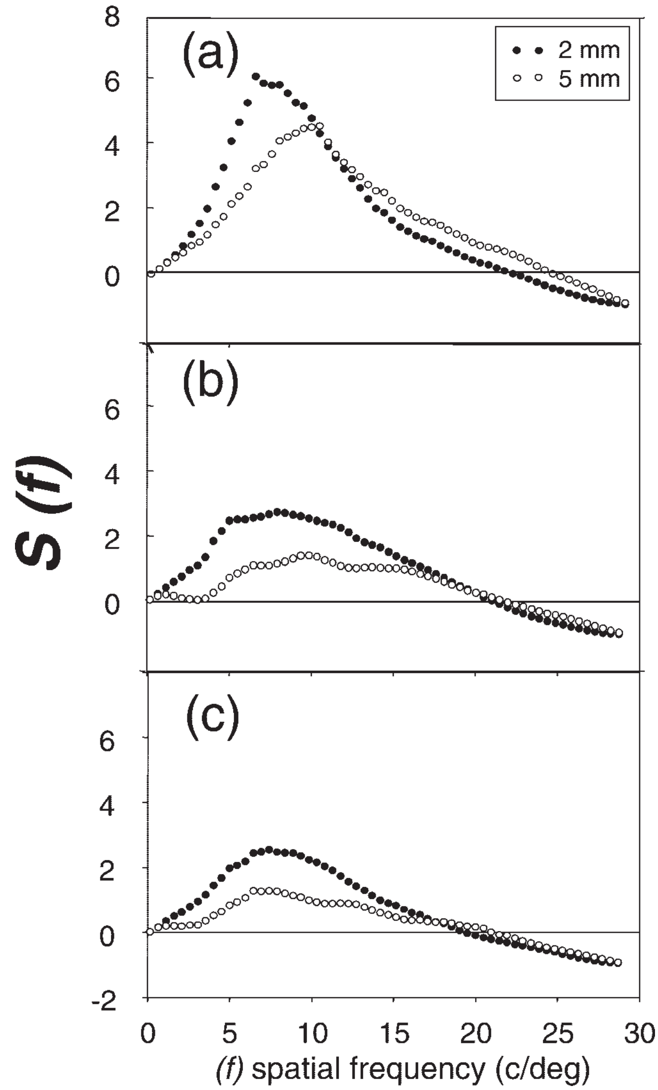

FIGURE 9. *S*(*f*) for 2- and 5-mm pupil diameter in MTFs averaged for all subjects in the older subject group (**a**); the eyes after post-LASIK refractive surgery (**b**) and after IOL implantation (**c**).

only had access to a small number of acuity data in this study, further research in this area is necessary to fully confirm this tendency.

DISCUSSION

We have compared the retinal image quality obtained with DP and HS wavefront sensor instruments. We applied both techniques in four groups of subjects having a different contribution of aberrations and scattering. The estimates of the retinal images were compared through the MTF, the ratio of MTFs

TABLE 1. SR_{HS-DP} in the Study Groups

	2 mm Pupil	5 mm Pupil
(a) Control group	0.188 ± 0.048	0.122 ± 0.039
(b) Older subjects group	0.512 ± 0.094	0.36 ± 0.17
(c) Post-LASIK group	0.36 ± 0.14	0.25 ± 0.20
(d) IOL group	0.38 ± 0.15	0.214 ± 0.064

Data are the mean ± SD.

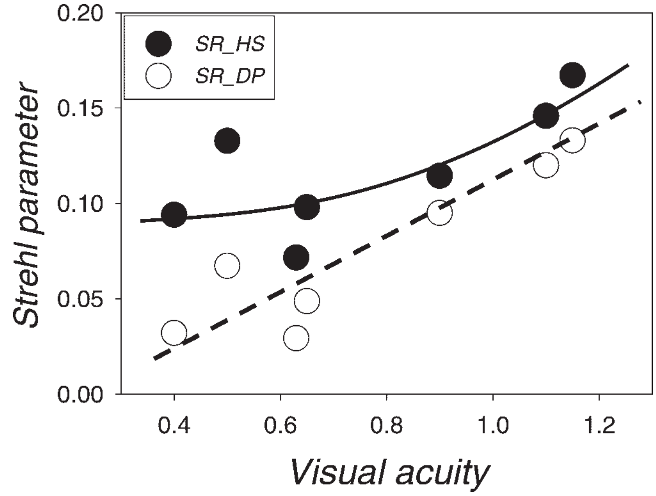

FIGURE 10. Visual acuity (decimal) as a function of the Strehl parameter obtained from HS (*solid circles*) and from DP for 2-mm pupil diameter. For eyes with higher visual acuity, both parameters are similar; however, for the eyes with lower acuity, the DP estimates predict better the drop in visual acuity. *Dashed line*: the linear fit to the DP data; *solid line*: the quadratic fit to the HS data.

(*S*(*f*)), and a single parameter (SR_{HS-DP}). This parameter provides information on the relative impact of an increased intraocular scatter on the retinal image. This parameter could range from 0, showing identical HS and DP contributions and suggesting an eye only affected by low and midorder aberrations, to 1, where the eye presents a complete lack of transparency, making scatter the predominant factor. In the group of normal young subjects (used as a control), we found a small, although not zero, value of this parameter, and the dispersion of data was relatively small. This indicates that in normal young eyes, HS and DP provide similar estimates of image quality, as should correspond to eyes with a minor contribution of scatter. However, this situation was not the case in other eyes. More notably in some older eyes presenting early stages of cataract, whereas the HS still was able to provide with an estimate of the retinal image, this was significantly better than the direct DP measurement. This is a clear example of an eye, affected by scatter, for which wavefront may fail to produce an overestimation of the image quality. Other types of eyes also showed differences in both methods. In these cases, eyes post-LASIK and those with IOLs also presented a larger variability. This could simply indicate a different level of scatter due to differences in the degree of corneal haze or different level of possible capsule opacification.

These results clearly suggest that in those cases in which the level of intraocular scatter could be higher than normal, additional direct measurements of the retinal image quality should be required beyond wavefront sensing. This is particularly important since what is actually well correlated with quality of vision is the quality of the retinal image and not aberrations. Investigators in other recent studies[37] that involved the DP approach have suggested this potential for the technique.

We should notice that the values of the parameter were lower for a 5-mm than for a 2-mm pupil diameter. This difference may simply indicate that the relative importance of scattering compared with aberrations decreased with pupil size in all the groups. Therefore, the amount of diffused light in DP images increased more slowly than aberrations did with pupil diameter.

The DP image provides complete information on the ocular optics, but also that concerning the retinal reflection. One possible drawback of the DP approach could be the unknown effect of retinal scattering. Previous experiments[38] recoding simultaneously DP images at different eccentricities suggested that retinal scatter affects slightly the DP images. In any case, the differences in this study for the control group could in some part come from this effect. Other factors potentially affecting the DP estimates is the polarized state of the incident light. This issue was studied previously in detail[39] and we found that the DP retinal image was nearly independent of the state of polarization of the incident light (in the first pass). In our case, linear polarized light was used. However, different estimates of the retinal image quality were obtained for combinations of polarization states in both the first and the second pass, and this should be considered in the instrument design.

In summary, we showed that the combined use of HS and DP allows differentiation of the relative contributions of aberrations and scattering in different eyes. This is a powerful approach, especially in those cases in which wavefront sensor provides good estimate of the image quality, but the subjects present a poor quality of vision. The use of the DP technique could be of potential use in a large variety of clinical situations: such as postrefractive surgery management, halo, and dazzle quantification, and early diagnosis of cataract.

References

1. Porter J, Guirao A, Cox IG, Williams DR. Monochromatic aberrations of the human eye in a large population. *J Opt Soc Am A*. 2001;18:1793–1803.
2. Thibos LN, Hong X, Bradley A, Cheng X. Statistical variation of aberration structure and image quality in a normal population of healthy eyes. *J Opt Soc Am A*. 2002;19:2329–2348.
3. Castejón-Mochón JF, López N, Benito A, Artal P. Ocular wave-front aberration statistics in a normal young population. *Vision Res*. 2002;42:1611–1617.
4. Moreno-Barriuso E, Merayo-Lloves J, Marcos S, Navarro R, Llorente L, Barbero S. Ocular aberrations before and after corneal refractive surgery: LASIK induced changes measured with laser ray tracing. *Invest Ophthalmol Vis Sci*. 2001;42:1396–1403.
5. Artal, P, Guirao A, Berrio E, Williams DR. Compensation of corneal aberrations by the internal optics in the human eye. *J Vis* 2001;1: 1–8.
6. Artal P, Berrio E, Guirao A, Piers P. Contribution of the cornea and internal surfaces to the change of ocular aberrations with age. *J Opt Soc Am A*. 2002;19:137–143.
7. Flamant F. Étude de la repartition de lumière dans l'image rétinienne d'une fente. *Rev Opt.* 1955;34:433–459.
8. Campbell FW, Gubisch, RW. Optical quality of the human eye. *J Physiol*. 1966;186:558–578.
9. Arnulf A, Santamaría J and Bescós J. A cinematrographic method for the dynamic study of the image formation by the human eye: microfluctuations of the accommodation. *J Opt*. 1981;12:123–128.
10. Santamaría J, Artal P, Bescos J. Determination of the point-spread function of human eyes using a hybrid optical-digital method. *J Opt Soc Am A*. 1987;4:1109–1114.
11. Artal P, Ferro M, Miranda I, Navarro R. Effects of aging in retinal image quality. *J Opt Soc Am A*. 1993;10:1656–1662.
12. Guirao A, González C, Redondo M, Geraghty E, Norrby S, Artal P. Average optical performance of the human eye as a function of age in a normal population. *Invest Ophthalmol Vis Sci*. 1999;40:203–213.
13. Pujol J, Gispets J, Arjona M. Optical performance in eyes wearing two multifocal contact lenses design. *Ophthalmic Physiol Opt*. 2003;23:347–360.
14. Artal P, Marcos S, Navarro R, Miranda I, Ferro M. Through focus image quality of eyes implanted with monofocal and multifocal intraocular lenses. *Opt Eng*. 1995;34:772–779.
15. Guirao A, Redondo M, Geraghty E, Piers P, Norrby S, Artal P. Corneal optical aberrations and retinal image quality in patients in whom monofocal intraocular lenses were implanted. *Arch Ophthalmol*. 2002;120:1143–1151.
16. Fernández EJ, Iglesias I, Artal P. Closed-loop adaptive optics in the human eye. *Opt Lett*. 2001;26:746–748.
17. Hofer H, Chen L, Yoon GY, Singer B, Yamauchi Y, Williams DR. Performance of the Rochester 2nd generation adaptive optics system for the eye. *Optics Expr*. 2001;8:631–643.
18. Artal P, Chen L, Fernández EJ, Singer B, Manzanera S, Williams DR. Neural compensation for the eye's optical aberrations. *J Vis*. 2004; 4:281–287.
19. Piers PA, Fernández EJ, Manzanera S, Norrby S, Artal P. Adaptive optics simulation of intraocular lenses with modified spherical aberration. *Invest Ophthalmol Vis Sci*. 2004;45:4601–4610.
20. Walsh G, Charman WN, Howland HC. Objective technique for the determination of monochromatic aberrations of the eye. *J Opt Soc Am A*. 1984;1:987–992.
21. He JC, Marcos S, Webb RH, Burns SA. Measurement of the wave-front aberrations by a fast psychophysical procedure. *J Opt Soc Am A*. 1998;15:2449–2456.
22. Navarro R, Moreno-Barriuso E. Laser ray-tracing method for optical testing. *Opt Lett*. 1999;24:951–953.
23. Iglesias I, Berrio E, Artal P. Estimates of the ocular wave aberration from pairs of double pass retinal images. *J Opt Soc Am A*. 1998; 15:2466–2476.
24. Iglesias I, Ragazzoni R, Julien Y, Artal P. Extended source pyramid wave-front sensor for the human eye. *Opt Expr*. 2002;10:419–428.
25. Liang J, Grimm B, Goelz S, Bille JF. Objective measurement of the WA's aberration of the human eye with the use of a Hartmann-Shack sensor. *J Opt Soc Am A*. 1994;11:1949–1957.
26. Liang J, Williams DR. Aberrations and retinal image quality of the normal human eye. *J Opt Soc Am A*. 1997;14:2873–2883.
27. Prieto PM, Vargas-Martín F, Goelz S, Artal P. Analysis of the performance of the Hartmann-Shack sensor in the human eye. *J Opt Soc Am A*. 2000;17:1388–1398.
28. Allen MJ, Vos JJ. Ocular scattered light and visual performance as a function of age. *Am J Optom Physiol Opt*. 1967;44:717–727.
29. Beckman C, Hard S, Abrahamsson M, Sjöstrand J. Evaluation of a clinical glare test based on estimation of intraocular light scatter. *Optom Vis Sci*. 1991;68:881–887.
30. Ansari RR. Ocular static and dynamic light scattering: a noninvasive diagnostic tool for eye research and clinical practice. *J Biomed Opt*. 2004;9:22–37.
31. Fujikado T, Kuroda T, Maeda N, et al. Light scatter and optical aberrations as objective parameters to predict deterioration in patients with cataract. *J Cataract Refract Surg*. 2004;30:1198–1208.
32. Artal P, Iglesias I, López N, Green DG. Double-pass measurements of the retinal image quality with unequal entrance and exit pupil sizes and the reversibility of the eye's optical system. *J Opt Soc Am A*. 1995;12:2358–2366.
33. Artal P, Marcos S, Navarro R, Williams DR. Odd aberrations and double-pass measurements of retinal image quality. *J Opt Soc Am A*. 1995;12:195–201.
34. Güell JL, Pujol J, Arjona M, Diaz-Douton F, Artal P. OQAS: A new instrument for an objective clinical evaluation of the ocular optical quality. *J Cataract Refract Surg*. 2004;30:1598–1599.
35. Lopez N, Artal P. Comparison of double-pass estimates of the retinal image quality obtained with green and near-infrared light. *J Opt Soc Am A*. 1997;14:961–971.
36. Noll RJ. Zernile polynomials and atmospheric turbulence. *J Opt Soc Am*. 1976;3:207–211.
37. Kobayashi K, Shibutani M, Takeuchi G, et al. Calculation of ocular single-pass modulation transfer function and retinal image simulation from measurements of the polarized double-pass ocular point. *J Biomed Opt*. 2004;9:154–161.
38. Artal P, Navarro R. Simultaneous measurement of 2-point spread functions at different location across the human fovea. *App Opt*. 1992;19:3646–3656.
39. Bueno J, Artal P. Polarization and retinal image quality estimates in the human eye. *J Opt Soc Am A*. 2001;18:489–496.