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Measuring the accommodative response with a double-pass system: Comparison with the Hartmann-Shack technique

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ABSTRACT

The current study aims at analysing the suitability of the double-pass technique in measuring the accommodative response. A custom-built setup which allowed simultaneous double-pass and Hartmann-Shack measurements was used. Several metrics to assess the accommodative response were tested and compared. In order to validate double-pass based measurements, the accommodative response was measured in 10 young adults under monocular viewing conditions with an open field fixation test. Accommodation was stimulated with the push up method in the 0–5 diopters (D) range with a 1-D step. We found no significant differences among accommodative response measurements obtained with the several metrics compared in the double-pass and the Hartmann-Shack technique. In addition, differences between the double-pass and Hartmann-Shack techniques were not statistically significant. However, we obtained slightly higher values in the measured accommodative response with the double-pass system than those usually reported by other authors. The double-pass technique takes into account all factors influencing retinal image quality. Consequently, we consider this technique as a potential powerful candidate for the analysis of accommodation.

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1. Introduction

Accommodation, defined as the dioptric adjustment of the crystalline lens of the eye (Keeney, Hagman, & Fratello, 1995), is the mechanism that allows people to see clearly at different distances. Measurement of accommodation is crucial for several reasons; presbyopia, the progressive loss of amplitude of accommodation (Atchison, 1995), is a physiological process affecting all the population; some diseases, such as accommodative insufficiency, affect the accommodative system (Cacho et al., 2002); in other disorders, such as convergence insufficiency, accommodation can be a diagnostic criterion (Arnoldi & Reynolds, 2007). It has been also suggested that the retinal blur due to accommodative error might be a factor influencing myopia development (Gwiazda et al., 1995). Moreover, there has been an increasing interest lately on techniques that restore accommodative ability in people with presbyopia (Glasser, 2006).

Accommodation is usually measured with simple subjective techniques based on increasing the accommodative demand of a fixation test until it begins to blur (Rabbetts, 2007). These techniques have generally provided an overestimated measured accommodation in comparison with objective techniques (Wold et al., 2003) due to the depth of focus. The depth of focus that people experience may be influenced by many factors, namely pupil size, magnification, character size and instructions given (Atchison, Campbell, & McCabe, 1994; Atchison, Charman, & Woods, 1997; Rosenfield & Cohen, 1995; Wang & Ciuffreda, 2006).

Of all objective techniques used to measure accommodation, dynamic retinoscopy (Campbell, Benjamin, & Howland, 1998) is the most widely used in daily clinical practice. However, its interpretation depends on the point of view of the examiner and it is difficult to carry out.

Autorefractors have also been used to measure accommodation and higher accommodative response measurements are often found when compared with dynamic retinoscopy (Rosenfield et al., 1996). Specifically, the Canon Autoref R-1 autorefractor (McBrien & Millodot, 1985), with an open field allowing a more natural stimulation and accurate response due to the proximity cue (Rosenfield & Gilmartin, 1990), has been used in several studies (Abbott, Schmid, & Strang, 1998; Heron, Charman, & Gray, 1999; Kalsi, Heron, & Charman, 2001; McBrien & Millodot, 1986).

Abbreviations: MTF, modulation transfer function; $IMAX_{DP}$, the peak of maximum intensity of the double-pass image; $FWHM_{DP}$, the full width at half maximum of the double-pass image; MTF_{DP}, the volume under the modulation transfer function of the double-pass image; MTF_{HS}, the volume under the modulation transfer function of the Hartmann Shack image; DEF_{HS}, defocus calculated from the Zernike polynomials corresponding to the Hartmann-Shack image; cpd, cycles per degree.

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However, some authors have pointed out that this autorefractor is affected by spherical aberration (Collins, 2001), which is particularly important since spherical aberration changes during accommodation (Li et al., 2011). The Canon Autoref R-1 autorefractor is no longer available, and some other alternatives which also make use of an open field configuration are currently being used to assess accommodative response (Davies et al., 2003; Mallen et al., 2001; Sheppard & Davies, 2010; Win-Hall & Glasser, 2008; Wolffsohn et al., 2006). Furthermore, Seidemann and co-workers highlighted the great variability of results when measuring lag of accommodation using autorefractors (Seidemann & Schaeffel, 2003), and their measurements using photorefraction were in the lower range of those previously published.

Wavefront sensors have also been used for assessing accommodation by means of the defocus measured from aberrations (Win-Hall & Glasser, 2008) or the retinal image quality calculated from the wavefront (Tarrant, Roorda, & Wildsoet, 2010). The aberrometric measurements have shown that the spherical aberration could be responsible for a false lag of accommodation, since a certain amount of defocus could be necessary to enhance retinal image quality (Buehren & Collins, 2006; Plainis, Ginis, & Pallikaris, 2005).

Finally, the double-pass technique, based on recording images of a point-source object after reflection on the retina and a double pass through the ocular media (Santamaría, Artal, & Bescos, 1987), has been widely used in daily clinical practice to assess retinal image quality in patients with uveitis (Nanavaty et al., 2011) and keratitis (Jiménez et al., 2009), patients having refractive surgery such as LASIK (Saad, Saab, & Gatinel, 2010; Vilaseca et al., 2009, 2010) and PRK (Ondategui et al., 2011), and patients with intraocular lenses (IOLs) (Vilaseca et al., 2009). It has been also applied to the study of accommodation (López-Gil, Iglesias, & Artal, 1998); nevertheless, this study focused mainly on the comparison of the retinal image quality of the accommodated and unaccommodated eye rather than on the assessment of the accommodative response.

The main goal of this study is to measure the accommodative response with the double-pass technique comparing the results with those obtained by means of the Hartmann-Shack technique. To our knowledge this has not been done to date. This technique takes into account every factor influencing retinal image quality (Díaz-Doutón et al., 2006). Its use in accommodative response measurement might contribute to the analysis of accommodation, providing a novel assessment method and a deeper insight into this visual property. With this aim, the accommodative response was measured by means of a device consisting simultaneously of a double-pass and a Hartmann-Shack system. Firstly, we analyzed independently for each technique if the quality metrics used for assessing the accommodative response had some influence on the results achieved; secondly, we compared the two datasets obtained to check if the results provided by the double-pass system were in agreement with the results of the Hartmann-Shack sensor. Finally, we show the whole range of accommodative response measurements assessed with the double-pass images to prove the validity of this technique as a means of assessing the accommodative response of the eye.

2. Materials and methods

2.1. Subjects

This prospective study was conducted on healthy young adults recruited from the staff and students of the Centre for Sensors, Instruments and Systems Development (CD6) of the Universitat Politècnica de Catalunya (UPC). All subjects gave their written informed consent after receiving a written and verbal explanation of the nature and the aims of the study. The research followed the tenets of the Declaration of Helsinki and was approved by the Ethics Committee.

The criteria for inclusion were as follows: best spectacle-corrected visual acuity of 20/20 or better, and no history of any ocular condition, surgery and/or pharmacological treatment. Furthermore, only subjects with a spherical refractive error from −3.00 to +3.00 D, a cylinder below 1.00 D, and a pupil diameter of 4 mm or more, as this was the value used in the measurements performed with the double-pass and Hartmann-Shack systems, were included in the study.

Ten subjects, seven male and three female, were eventually enrolled in the study. Measurements were only carried out in one eye: due to the configuration setup, the left eye was chosen in all cases. The mean age (±standard deviation [SD]) of the population was 27.90 ± 2.33 years (range: 23–31 years). The mean decimal uncorrected visual acuity was 0.89 ± 0.48 (range: 0.05–1.20), and the mean best spectacle-corrected visual acuity was 1.16 ± 0.08 (range: 1.00–1.20). The mean spherical refractive error was −0.50 ± 1.45 diopters (D) (range: +0.75 to −3.00 D), and the mean cylindrical refraction was −0.30 ± 0.20 D (range: 0.00 to −0.50 D).

2.2. Instrumentation

Accommodative response measurements were performed using an experimental setup developed in our laboratory combining the double-pass (Santamaría, Artal, & Bescos, 1987) and Hartmann-Shack (Liang et al., 1994; Prieto et al., 2000) techniques, as shown in Fig. 1.

In the first pass, a point source is projected on the retina of the subject. An infrared laser diode (LD, $\lambda = 780$ nm) coupled to an optical fiber is collimated and passes through a 2 mm diameter diaphragm, which acts as the entrance pupil (EP) of the system and is conjugated to the subject's pupil plane. After retinal reflection and a double pass through the ocular media, double-pass and Hartmann-Shack images are recorded with digital CCD (charge-coupled device) cameras (CCD DP and CCD HS). The second pass is divided in two paths by means of two beam splitters (BS1, BS2), which allow the simultaneous acquisition of double-pass and Hartmann-Shack images. In the case of the double-pass path, a 4-mm diameter diaphragm conjugated to the subject's pupil plane acts as the exit pupil of the system (ExP). The use of different entrance and exit pupils is known as asymmetric double-pass configuration (Artal, Iglesias, et al., 1995) and allows odd aberrations to be measured (Artal, Marcos, et al., 1995). In the case of the Hartmann-Shack path, a 0.5× magnification is achieved by means of a telescope (L4, L5) and an array of microlenses (AMs) conjugated with the pupil of the eye and with the CCD sensor at its focal plane is used. Thus, light coming from the subject's retina forms a mosaic of spots, each of them corresponding to a microlens. An unaberrated wavefront would yield a regular mosaic of spots on the CCD. When the wavefront is aberrated, the spot distribution on the CCD 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 can be computed and expressed as a Zernike polynomial expansion. In our system, each microlens had an effective aperture size of 0.2 mm at the pupil plane and a focal length of 6.3 mm.

A Badal system consisting of two 100 mm focal length lenses (L2, L3) and two mirrors (M2, M3) is used to change the vergence of the laser beam in both first and second passes. Moreover, a fixation test (FT) with a black and white Maltese cross presented on a monitor screen under low light illumination conditions, which is often used in accommodation measurements (Bharadwaj & Schor, 2005; Gambra et al., 2009; Mordi & Ciuffreda, 1998), is shown to the subject through open field. The FT size was 135 × 135 mm for far distance and 35 × 35 mm for near accommodative

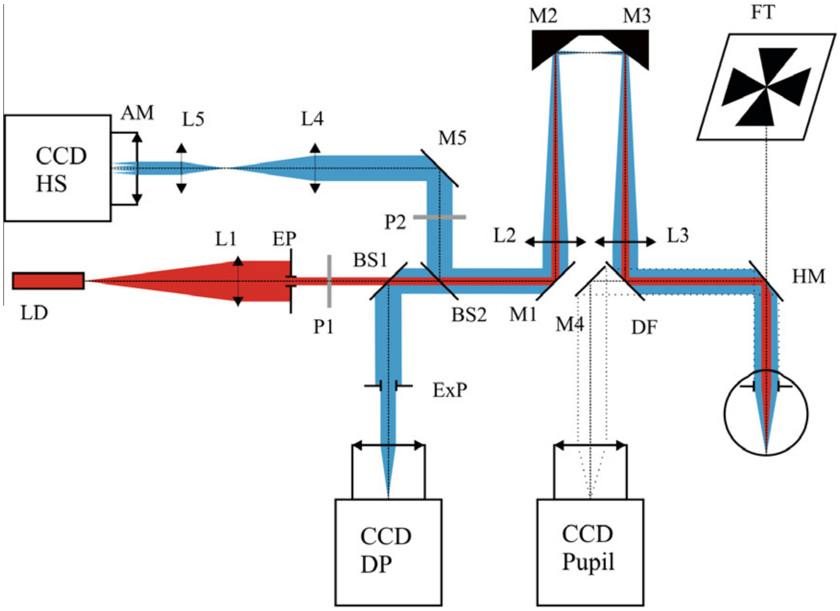

Fig. 1. Diagram of the setup used for the double-pass and Hartmann-Shack measurements. LD: Laser diode; L1, L2, L3, L4, L5: lenses; M1, M2, M3, M4: mirrors, BS1, BS2: beam splitters; DF: dichroic filter; HM: hot mirror; EP: entrance pupil; ExP: exit pupil; P1, P2: polarizers; FT: fixation test; AM: array of microlenses; CCD-DP, CCD-HS, CCD-Pupil: CCD cameras used for the double-pass and Hartmann-Shack measurements and pupil monitoring, respectively.

stimulation. The luminance of the FT was of 20 cd/m^2. A hot mirror (HM) that reflects infrared and transmits visible light is the only optical element placed in front of the subject, thus simulating real visual conditions.

A third CCD camera (CCD Pupil) is used for pupil monitoring and centring. The subject's eye is illuminated with a set of light-emitting diodes which emit at 1050 nm. A dichroic filter (DF) is used to separate light coming from the retina ($\lambda = 780$ nm) from that coming from the pupil plane ($\lambda = 1050$ nm).

The system includes crossed polarizers (P1, P2) to remove the corneal reflection from the Hartmann-Shack images acquired. Light arriving at the eye surface is linearly polarized. Afterwards, light reflected on the cornea is kept polarized while that coming into the eye suffers a certain amount of depolarization (van Blokland, 1985). Consequently, corneal reflection is rejected by means of P2, while light coming from the retina forms the Hartmann-Shack image. It has been already shown (Marcos et al., 2002) that polarization does not affect aberration measurements when using the Hartmann-Shack technique. In the case of the double-pass technique, the image quality is only slightly affected if polarized light is used in the first path but not in the second one (Bueno & Artal, 1999, 2001).

The system was calibrated calculating the difference between controlled and measured defocus and astigmatism. When measuring defocus the mean error in the double-pass system was of 0.01 ± 0.06 D, meanwhile it was of −0.02 ± 0.02 D in the Hartmann-Shack system. In the case of astigmatism, the mean error calculated in the Hartmann-Shack system was of 0.04 ± 0.02 D. It must be taken into account that the double-pass system does not assess the astigmatism.

2.3. Measurement procedures

All subjects underwent an optometric examination performed by the same qualified examiner to analyse their left eye. Refractive state was measured by means of the Grand Seiko Auto Ref/Keratometer WAM-5500 (Sheppard & Davies, 2010), streak retinoscopy and subjective refraction. Uncorrected visual acuity, stenopeic visual acuity, and best-spectacle-corrected visual acuity were also evaluated.

Subjects were placed in front of the setup with their head on a chinrest, wearing their subjective refraction on the left eye and with the right eye occluded. They were instructed to fix and try to see clearly on the fixation test. Accommodation was stimulated by means of the push up method in the range from 0 to 5 D with a 1-D step.

For every accommodative stimulation step, i.e. for 0, 1, 2, 3, 4 and 5 D, the Badal system was moved looking for the best double-pass image. This was determined subjectively by the examiner while seeing live video images, choosing at the end of the process a specific image called the preliminary best double-pass image. Subsequently, a through focus scanning was performed with the Badal system in the range from +0.5 to −0.5 D, in 0.125 D steps, in relation to the preliminary best double-pass image previously determined. In every step of the scanning a double-pass image was recorded. Moreover, a Hartmann-Shack image was also recorded at the central point, where the best preliminary double-pass image was found. The scanning was repeated four consecutive times in order to reduce the effect of accommodative microfluctuations, and the accommodative response was calculated as the mean of the performed series. The total duration of the measurement for an accommodative stimulation step was less than 20 s.

2.4. Accommodative response measurements

In the case of the double-pass technique, the accommodative response was calculated from the images recorded with the through focus scanning described above. The accommodative response was calculated aiming at the best double-pass image, whose vergence was then associated with the accommodative response value. To determine the best double-pass image, three different metrics were used: the peak of maximum intensity of the double-pass image (IMAX_{DP}), the full width at half maximum of the double-pass image (FWHM_{DP}), and finally the volume under the modulation transfer function (MTF_{DP}). The modulation transfer function (MTF) can be easily computed from the double-pass image by Fourier transformation, taking into account that the first pass of the double-pass system can be considered limited by diffraction, since a 2 mm entrance pupil is used (Navarro & Losada, 1995). The vergence corresponding to the best double-pass image selected by means of any of the used metrics has been taken as the accommodative response of the subject.

In Hartmann-Shack measurements, the accommodative response was measured taking into account two different criteria: firstly, it was selected as the defocus maximizing the volume under the MTF ($\mathrm{MTF_{HS}}$), which can be also computed from the Hartmann-Shack image as already described by other authors (Prieto et al., 2000). For this purpose, an artificial through focus scanning similar to that performed with the double-pass images was simulated by computationally adding or subtracting the defocus term (c_2^0) to the wavefront aberration pattern calculated from the unique recorded Hartmann-Shack image; secondly, it was calculated from the Zernike polynomials corresponding to the Hartmann-Shack image recorded at the central point as that corresponding to defocus and spherical aberrations ($\mathrm{DEF_{HS}}$), calculated up to the 6th order (Thibos et al., 2004):

$$\mathrm{DEF_{HS}} = \frac{-c_2^0 4\sqrt{3} + c_4^0 12\sqrt{5} - c_6^0 24\sqrt{7}}{r^2} \tag{1}$$

where c_2^0, c_4^0 and c_6^0 are the Zernike terms expressed in the nomenclature recommended by the Optical Society of America (Thibos et al., 2002), and r is the pupil radius in millimeters.

In Fig. 2, the through focus scanning process in which double-pass images at different vergences are recorded is shown. The wavefront aberration pattern corresponding to the unique Hartmann-Shack image recorded at the central point is also plotted, as well as the rest of simulated patterns calculated by adding or subtracting a certain amount of defocus.

Finally, when measuring accommodative response it must be taken into account that one of the values of the different accommodative stimulations will offset the system, as other authors have done (Gambra et al., 2009). Due to the lead of accommodation it cannot be stated that AR is 0 D at AS 0 D. Since some authors assume that the cross over point is close to the tonic accommodation (Charman, 1999) and this is considered to be near 1 D (Maddock et al., 1981; McBrien & Millodot, 1987), we have considered that there is no accommodative error at this value. Thus, the accommodative response measurements are shifted in order to fulfil this assumption. This shift of the raw data also entails a chromatic aberration correction, as we assume no accommodative error using visible light at 1 D of stimulation.

As subjects were corrected with spectacles during measurements, lens effectivity formulae were also applied both for accommodation stimulations and response calculations, as shown in Eqs. (2) and (3). Specifically, we applied the Mutti's effectivity formulae (Buehren & Collins, 2006; Mutti et al., 2000),

$$\mathrm{AS} = \frac{1}{\frac{1}{\frac{1}{D_{vertex} - D_{Test}} + P_{lens}} - D_{vertex}} - Rx \tag{2}$$

$$\mathrm{AR} = \frac{1}{\frac{1}{\frac{1}{\frac{1}{RawAR} + D_{vertex}} + P_{lens}} - D_{vertex}} - Rx \tag{3}$$

where AS is the accommodative stimulation, AR is the accommodative response, Rx is the subjective refraction of the subject, P_{lens} is the power of the trial lens and $RawAR$ is the raw measured accommodative response (in diopters). D_{vertex} is the vertex distance and D_{Test} is the test distance (in meters).

2.5. Statistics

Statistical analysis was performed using commercial SPSS software for Windows (version 17.0, SPSS, Chicago, IL). A p value of 0.05 was considered significant.

The Kolmogorov–Smirnov (K–S) test was used to evaluate the normal distribution of all variables analysed, i.e. the accommodative response measurements obtained by means of the double-pass and Hartmann-Shack techniques using different metrics. The mean (±SD) is given for each of them.

The validity of our method as the ability to measure correctly the accommodative response of the eye was tested from different points of view. Firstly, correlation coefficients were used to compare accommodative response measurements provided by the different techniques. Pearson's correlation coefficient and its significance is given for each case.

A Bland and Altman analysis (Altman & Bland, 1983; Bland & Altman, 1986) was subsequently performed to study the agreement between techniques. This method plots the mean difference against the mean value and the corresponding 95% confidence limits, defined as 1.96 times the standard deviation (SD) of the mean difference, within which 95% of the differences between measurements are expected to lie. According to this method, the charts can be used to evaluate any relationship in the differences between the accommodative response measurements assessed with the different techniques. To evaluate if there was any tendency in the differences to vary in any systematic manner over the range of measurements, the Pearson correlation coefficient and its significance were also used in the Bland and Altman plots.

Finally, a paired sample t test was carried out to analyse if there were significant differences between the accommodative response measurements reported by the techniques evaluated.

3. Results

3.1. Analysis of the accommodative response measurements in relation to the metrics used

The accommodative response measurements assessed by means of different metrics must be compared since they may have

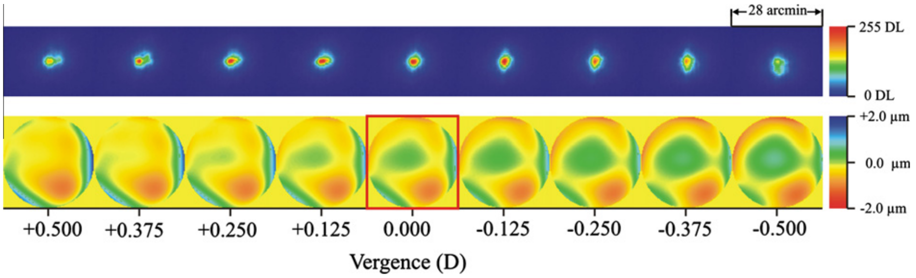

Fig. 2. Top: Example of double-pass images acquired along the through focus scanning (DL = digital level). Bottom: Hartmann-Shack wavefront aberration pattern recorded at the central point (framed in a red box), as well as the simulated patterns computationally obtained by changing the defocus term (c_2^0). Labels of vergence are in diopters (D). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Comparison of accommodative response (AR) measurements using different metrics and the double-pass and Hartmann-Shack techniques. The mean difference (±SD) between pairs of metrics, the Pearson correlation coefficient and its significance between AR measurements, the Pearson correlation coefficient and its significance in the Bland and Altman plots and the paired sample *t* test results are shown.

	Mean difference ± SD (D)	Pearson correlation coefficient, *r* (*p*)	Bland and Altman Pearson correlation coefficient, *r* (*p*)	Paired sample *t* test (*p*)
DP				
$\mathrm{AR}_{\mathrm{IMAX}_{\mathrm{DP}}} - \mathrm{AR}_{\mathrm{FWHM}_{\mathrm{DP}}}$	0.04 ± 0.29	0.976 (<0.001)	−0.121 (0.317[a])	0.315[a]
$\mathrm{AR}_{\mathrm{IMAX}_{\mathrm{DP}}} - \mathrm{AR}_{\mathrm{MTF}_{\mathrm{DP}}}$	−0.05 ± 0.18	0.981 (<0.001)	0.034 (0.775[a])	0.672[a]
$\mathrm{AR}_{\mathrm{FWHM}_{\mathrm{DP}}} - \mathrm{AR}_{\mathrm{MTF}_{\mathrm{DP}}}$	−0.09 ± 0.29	0.976 (<0.001)	0.150 (0.213[a])	0.174[a]
HS				
$\mathrm{AR}_{\mathrm{MTF}_{\mathrm{HS}}} - \mathrm{AR}_{\mathrm{DEF}_{\mathrm{HS}}}$	−0.06 ± 0.40	0.969 (<0.001)	−0.035 (0.760[a])	0.264[a]

[a] No significant differences.

an impact on the final results achieved with the double-pass and the Hartmann-Shack techniques.

In the case of the double-pass technique, the quality metrics tested, IMAX$_{\mathrm{DP}}$, FWHM$_{\mathrm{DP}}$ and MTF$_{\mathrm{DP}}$, were compared by pairs. The mean difference among metrics, close to zero in all cases, is shown in Table 1. There was a strong correlation between accommodative response measurements provided by all methods, with significant Pearson correlation coefficients (Fig. 3, Table 1). In the Bland and Altman analysis (Fig. 4), most differences lied within the $\pm 1.96 * \mathrm{SD}$ range, and therefore a good agreement between metrics was inferred. Moreover, almost every outlier value corresponded to the same subject. In order to study if there was any dependence of the differences on the mean, we also calculated the existing correlations between the differences found against the average value. No significant correlations were found in this case and therefore we considered that there was no dependency of the difference between metrics with the accommodative response value (Table 1). Finally, after confirming the normal distribution of the accommodative response measurements in all cases with the K–S test ($p > 0.05$), we compared the measurements obtained by each technique with the paired sample *t* test, and no significant differences were found between metrics ($p > 0.05$) (Table 1).

In the case of the Hartmann-Shack technique, the two used metrics were MTF$_{\mathrm{HS}}$ and DEF$_{\mathrm{HS}}$. A significant Pearson correlation coefficient was also found in this case (Table 1 and Fig. 5). Fig. 6 shows the Bland and Altman analysis, where again almost every difference is found within the plotted confidence limits. As with the double-pass technique, no significant correlations were found in the Bland and Altman plots (Table 1). The K–S test confirmed a normal distribution of the measurements ($p > 0.05$), and no significant differences were found when comparing methods with the paired sample *t* test (Table 1).

Since no significant differences were found between tested metrics, the double-pass and Hartmann-Shack results compared hereafter are those obtained by means of the volume under the MTF, i.e. the MTF$_{\mathrm{DP}}$ and MTF$_{\mathrm{HS}}$, respectively. This metrics has been shown to be a good predictor of the refractive error by some authors (Guirao & Williams, 2003), and is computable using both techniques. It is therefore considered the most suitable for comparison purposes.

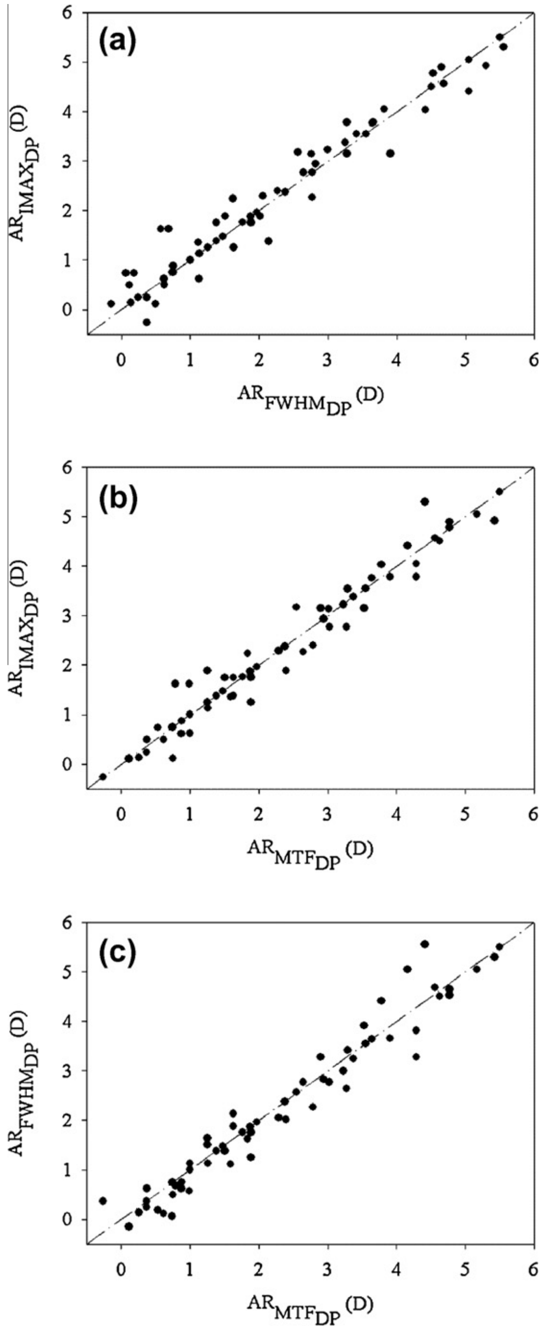

Fig. 3. Correlation of the accommodative response (AR) measurements obtained with the double-pass technique and the several metrics tested; (a) comparison between IMAX$_{\mathrm{DP}}$ and FWHM$_{\mathrm{DP}}$, (b) IMAX$_{\mathrm{DP}}$ and MTF$_{\mathrm{DP}}$ and (c) FWHM$_{\mathrm{DP}}$ and MTF$_{\mathrm{DP}}$ ($n = 60$; D: diopters).

3.2. Comparison of the double-pass and Hartmann-Shack accommodative response measurements

In this study, the performance of the double-pass and Hartmann-Shack techniques to measure the accommodation response of the eye were compared. Accommodative response measurements provided by both techniques using the volume under the MTF reported a mean absolute difference of 0.05 ± 0.24 D. In this case, the existing correlation between the results corresponding to the double-pass and Hartmann-Shack techniques was also investigated, as it had been previously done separately by each technique and the several metrics analysed. As shown in Fig. 7, there was a significant correlation between data ($r = 0.966$, $p < 0.001$).

Fig. 8 illustrates the Bland and Altman analysis when the accommodative response measurements provided by the double-pass and Hartmann-Shack techniques are compared. Most

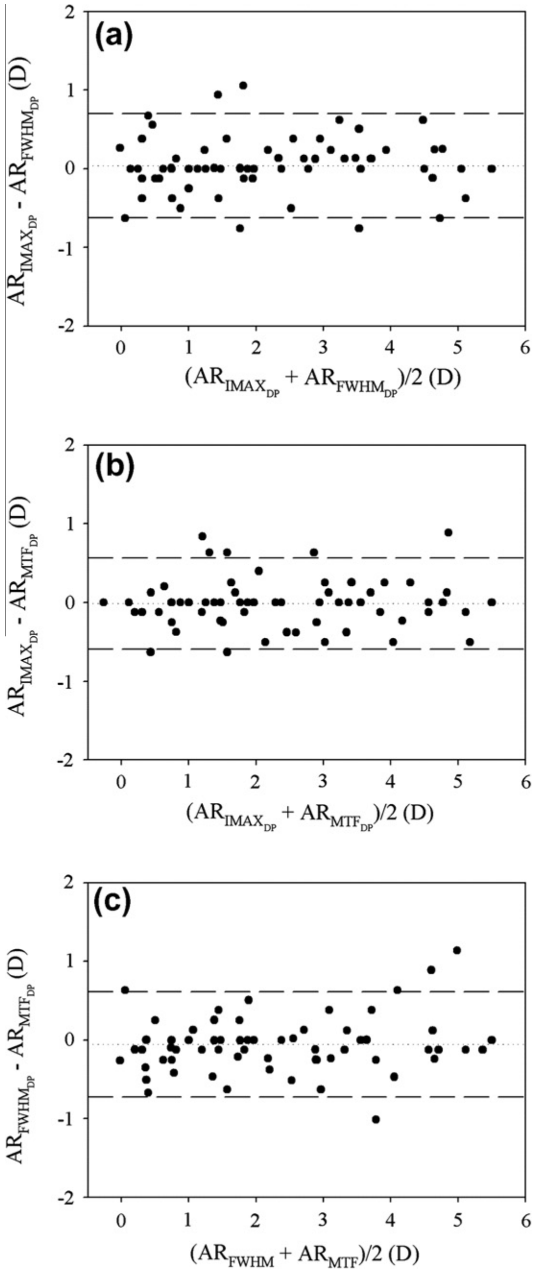

Fig. 4. Bland and Altman plots showing the mean of the differences of the accommodative response (AR) measurements and the 95% confidence limits (dashed line) when the several quality metrics tested are compared; (a) comparison between IMAX$_{DP}$ and FWHM$_{DP}$, (b) IMAX$_{DP}$ and MTF$_{DP}$ and (c) FWHM$_{DP}$ and MTF$_{DP}$ ($n = 60$; D: diopters).

differences are within the confidence limits. A weak and non-significant correlation was again obtained ($r = 0.002$, $p = 0.988$).

Finally, no significant differences in relation to the accommodative response between the double-pass and Hartmann-Shack methods by means of the paired sample t test were found ($p = 0.822$).

3.3. Accommodative response measurements

This section describes the accommodative response provided by means of the double-pass technique computed with the MTF$_{DP}$ metrics, since no significant differences were found with the different metrics analyzed.

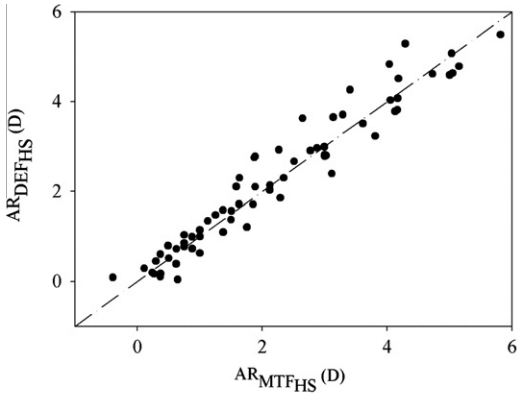

Fig. 5. Correlation of the accommodative response (AR) measurements obtained by means of Hartmann-Shack technique and the MTF$_{HS}$ and DEF$_{HS}$ quality metrics tested ($n = 60$; D: diopters).

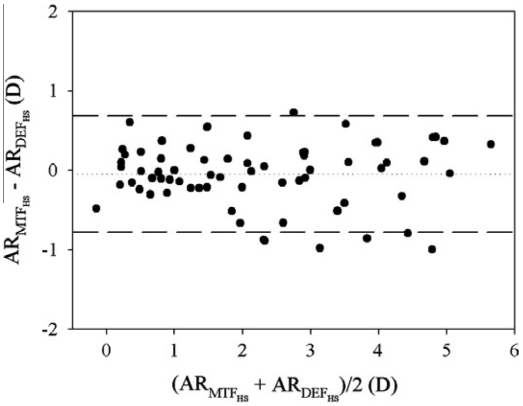

Fig. 6. Bland and Altman plots showing the mean of the differences of the accommodative response (AR) measurements and the 95% confidence limits (dashed line) when the MTF$_{HS}$ and DEF$_{HS}$ quality metrics tested are compared ($n = 60$; D: diopters).

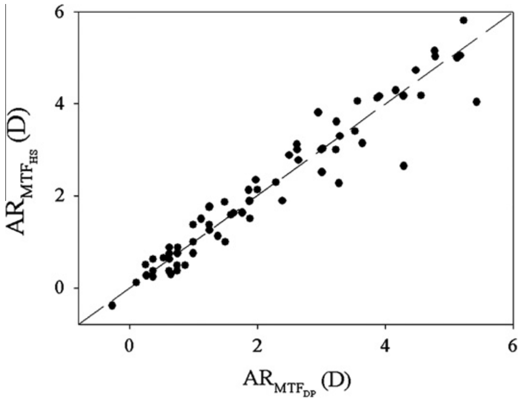

Fig. 7. Correlation of the accommodative response (AR) measurements obtained by means of double-pass and Hartmann-Shack techniques when using the MTF$_{DP}$ and MTF$_{HS}$ metrics ($n = 60$; D: diopters).

Fig. 9 shows the accommodative response curve with stimulation from 0 to 5 D: in the first accommodative stimulation steps there is a lead of accommodation, while after the cross over point the lag of accommodation increases in correlation to the stimulation.

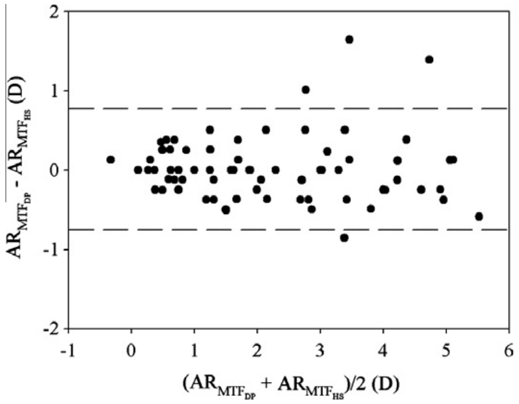

Fig. 8. illustrates the Bland and Altman analysis when the accommodative response measurements provided by the double-pass and Hartmann-Shack techniques are compared. Most differences are within the confidence limits. A weak and non-significant correlation was again obtained ($r = 0.002$, $p = 0.988$).

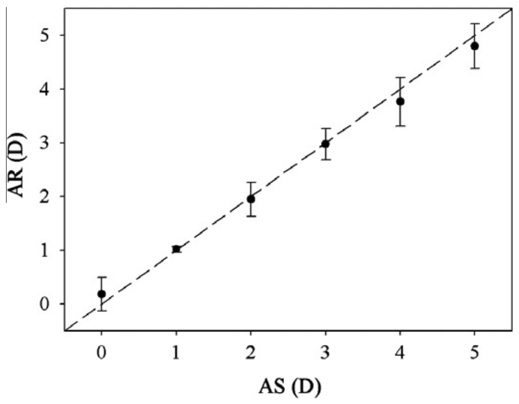

Fig. 9. Mean accommodative response (AR) for accommodative stimulation (AS) from 0 to 5 D measured with the double-pass technique when using the MTF_{DP} quality metrics (D: diopters). Dashed line indicates the line of equality.

An accurate accommodative response is obtained, with an average accommodative error of 0.24 D in the worst case, which corresponds to an accommodative stimulation of 4 D. Specifically, the mean accommodative responses (±SD) for the accommodative stimulations (from 0 to 5 D with a 1-D step) were 0.18 ± 0.31, 1.00 ± 0.00, 1.94 ± 0.31, 2.97 ± 0.29, 3.76 ± 0.45 and 4.80 ± 0.42 D. As it can be seen the lag of accommodation is slightly higher at 4 D stimulation than at 5 D, specifically 0.24 D and 0.20 D, but this differences are not statistically significant ($p > 0.05$). Moreover, other authors have found similar results when measuring the lag of accommodation using photorefraction (Seidemann & Schaeffel, 2003).

In far vision, i.e. with an AS of 0 D, the results obtained with the method proposed correlate very well with subjective refraction. A Pearson coefficient of 0.973 ($p < 0.001$) was obtained and no statistically significant differences between subjective and double-pass measurements were found when applying the *t* test ($p = 0.814$).

4. Discussion

The current study investigated the accommodative response measurement based on the retinal image quality obtained by means of a double-pass system. The results were compared with those obtained with the Hartmann-Shack technique, more widely in use, and also available in the built experimental setup. Moreover, several metrics based on different principles were used to compute the accommodative response from the images obtained, which in the case of the double-pass technique and to our knowledge had never been done previously, even for measuring the objective refraction of patients.

We did not find significant differences among metrics used in the case of the double-pass technique. The highest mean difference in terms of accommodative response was 0.09 D when comparing the $FWHM_{DP}$ and MTF_{DP} metrics.

When comparing the results for Hartmann-Shack measurements by means of the two metrics, we obtained a mean absolute difference of 0.06 D. However, the differences were not significant. In agreement with our results, other authors could not report significant differences at some accommodative stimulations (2 and 3 D). Nevertheless, they found statistically significant differences at other values of accommodative stimulation (4 and 5 D) (Tarrant, Roorda, & Wildsoet, 2010).

No significant differences between the double-pass and Hartman Shack techniques were found in terms of accommodative response, with a mean absolute difference of 0.05 D. Both techniques provide similar information, although each one has its own particularities. Double-pass images contain all the information on the optical quality of the eye up to the spatial frequency limited by the size of the entrance pupil, while in aberrometric measurements there is a lack of information on scattering and the number of computable higher-order aberrations is limited by the number of lenslets sampling in the pupil. Although the actual limitation of spatial frequency present in double-pass systems, similar configurations in terms of pupil sizes and wavelength have been widely used in former laboratory studies to analyse accommodation (López-Gil et al., 1998), optical and visual quality in eyes with decentered pupils (Artal, Marcos, Iglesias, & Green, 1996), peripheral refractive errors in young subjects (Seidemann et al., 2002) and off-axis monochromatic aberrations (Guirao & Artal, 1999). Moreover, many clinical studies which studied the optical quality in eyes with different ocular conditions and diseases were carried out with a commercially available double-pass system which uses the same pupil sizes and wavelength than those of this study (Jiménez et al., 2009; Nanavaty et al., 2011; Ondategui et al., 2011; Saad, Saab, & Gatinel, 2010; Vilaseca et al., 2009, 2010). Furthermore, Plainis when measuring accommodation with a Hartmann-Shack aberrometer used a weighting function peaking at a spatial frequency of 18 cycles per degree (cpd) (Plainis, Ginis, & Pallikaris, 2005).On the other hand, many studies that have studied the effect on accommodation of the stimulus spatial frequency took into account maximum values of 16 cpd (Charman & Heron, 1979; Taylor et al., 2009; Ward, 1987). This value is much lower than the cutoff frequency measured by our double-pass setup (45 cpd), thus proving the usefulness of the configuration used to account for accommodative responses again. Another difference between the double-pass and HS techniques is that double-pass through focus scanning needs from several image recording while in HS is enough with one image acquisition. However, it must be taken into account that this scanning is fast and can be performed in less than a second.

Finally, it should be emphasized that the accommodative error found, which was measured using a 4-mm pupil diameter, was lower than the values generally reported by other authors. Cacho and colleagues measured an accommodative error of 0.41, or 0.73 D for 2.5 D of stimulation using streak retinoscopy and the Nott or MEM technique, respectively (Cacho et al., 1999). He and colleagues measured an accommodative error of 0.31 D for a 3-D stimulation by means of an autorefractor (He et al., 2005), whereas we found a value of 0.03 D using the double-pass technique. For 4 D of accommodative stimulation we measured an error of 0.24 D. Seidemann and Schaeffel reported slightly higher errors (0.35 D) using photorefraction (Seidemann & Schaeffel, 2003). In addition, the accommodative error measured by other authors in emmetropic subjects by means of the Hartmann-Shack technique for the same accommodative stimulation was also higher, specifically of 1.2 D (Hazel, Cox, & Strang, 2003). Similarly to the current study, in this case the authors took into account the higher-order aberrations. A plausible hypothesis for the differences between theirs and our results can be attributed to their use of an internal fixation test in contrast to our open field configuration that simulates real viewing conditions. On the other hand, López-Gil and colleagues studied the retinal image quality of the accommodated eye and found very low accommodative errors when using a double-pass system: 0.11 D for 4 D of stimulation (López-Gil et al., 1998). Although using the same technique and a similar range of ages, the differences with our results could be explained by the fact that they worked with trained subjects, while we did not. Moreover, they only measured far (0 D) and near (4 D) conditions, while we measured intermediate distances. This could have made the measurements more tiring and caused less concentration in the individuals at the last accommodative stimulations.

In conclusion, the accommodative response measured with the double-pass technique is generally higher than previously reported. The reason for our lower accommodative error could be explained by all factors affecting the retinal image quality in a double-pass system. It has been suggested that one to one ideal response, with no accommodative error, does not always correspond to the best retinal image quality, and that a certain amount of accommodative error (measured defocus) is used to enhance the retinal image quality (Buehren & Collins, 2006; Plainis, Ginis, & Pallikaris, 2005). Using a Hartmann-Shack instrument, Tarrant, Roorda, and Wildsoet (2010) found higher accommodative responses when measurements were based on optical quality metrics rather than just on defocus. In this work the accommodative response based on the volume under the MTF was up to 0.4 D higher than that based on defocus, taking into account 5 D of stimulation and myopic subjects. Since double-pass based accommodative response measurements are based on retinal image quality and not defocus, this cannot be a source of error in our results. The results obtained in this study suggest the suitability of the double-pass system to measure accommodative response. Future studies should address the suitability of these measurements in older subjects.

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