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Comparison of the Adaptive Optics Vision Analyzer and the KR-1 W for measuring ocular wave aberrations

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Background: The aim was to assess the agreement in the measurement of ocular aberrations between a new Adaptive Optics Vision Analyzer (AOVA, Voptica, Murcia, Spain) and a commercial aberrometer (KR-1 W, Topcon, Tokyo, Japan), both based on the Hartmann–Shack technique.
Methods: One experienced examiner measured 29 healthy right eyes nine consecutive times with the two instruments. The individual Zernike coefficients and the root mean square (RMS) of each order from the second to the fifth order, the higher-order RMS (RMS_{HOA}), the total RMS (RMS_{TOT}) and the values of the spherical equivalent (M) and Jackson cross-cylinder (J_0 and J_{45}) were compared. All aberrations were computed for a 4.0 mm pupil diameter.
Results: Bland and Altman analysis showed good agreement between instruments and most of the parameters showed no statistically significant differences. Although the largest mean differences were obtained for the defocus coefficient C(2,0) and the spherical equivalent (M) with a mean difference (and standard deviation) of 0.190 ± 0.099 µm and -0.150 ± 0.188 D, respectively, they were clinically acceptable and significant correlations were found between the AOVA and KR-1 W for the major refractive components such as spherical equivalent ($r = 0.995$, $p < 0.001$), J_0 ($r = 0.964$, $p < 0.001$), J_{45} ($r = 0.901$, $p < 0.001$) and C(4,0) ($r = 0.575$, $p = 0.001$).
Conclusion: The results suggest good agreement between instruments. Accommodation and misalignment of the measurements may play a role in some of the statistically significant differences that were obtained, specifically for defocus C(2,0), vertical coma C(3,−1) and spherical aberration C(4,0) coefficients; however, these differences were clinically irrelevant.

Key words: agreement, ocular aberrations, refraction, wavefront aberrometers

Wavefront sensing has become part of daily clinical practice, specifically for refractive and cataract surgery and for screening and assessing ocular diseases that modify the ocular aberrometric pattern, such as keratoconus. Many instruments have been developed to assess ocular aberrations, the factor that most affects retinal image quality together with intraocular scattering.[1] The aberrometers based on the Hartmann–Shack technique[2,3] are the most widely used.

Thanks to new optical techniques such as adaptive optics technology,[4] it is now possible to measure refraction and higher-order aberrations and to correct and modify them in a non-invasive manner. A new clinical device, the Adaptive Optics Vision Analyzer (AOVA, Voptica, Murcia, Spain), includes a Hartmann–Shack aberrometer and an adaptive optics spatial light modulator. Spatial light modulators are active optical devices that work either in transmission or reflective modes and can change the amplitude, phase or polarisation of light waves in space and time. For wavefront manipulation purposes (for example, wavefront correction) control over the phase is required. Deformable mirrors can also be used for similar wavefront manipulations.

The AOVA can perform visual simulations, such as correcting and/or inducing certain aberrations, measure visual acuity, contrast sensitivity and glare, simulate different optics (lenses and refractive profiles) and combine optical and visual testing at any distance.

It is common practice to assess the accuracy of every new ophthalmic commercial instrument for repeatability, reproducibility, precision and reliability.[5–14] According to international standards,[15] precision and trueness describe the accuracy of a measurement method. Trueness refers to the closeness of agreement between a measurement and the true or accepted reference value; precision refers to the closeness of agreement between test results. The latter involves the concepts of repeatability and reproducibility. Note that in order to study trueness, the measurement method is assumed to be precise.

When an ophthalmic instrument becomes commercially available it is essential to compare its precision and agreement with other existing instruments. Accordingly, the aim of this study is to compare aberrometric data measured with the AOVA with the KR-1 W (Topcon, Tokyo, Japan), an established commercial wavefront analyser, also based on the Hartmann–Shack technique. The repeatability (precision) of both the AOVA[16] and the KR-1 W[12,13] have already been analysed. The root mean square of higher-order aberrations (RMS_{HOA}) in AOVA and KR-1 W of 0.078 and 0.014 µm, respectively, suggest that both devices provide reliable measurements. To our knowledge, no study has reported the agreement of the AOVA with another instrument.

METHODS

Subjects

This cross-sectional study was conducted on healthy subjects recruited from the staff and students of the Faculty of Optics and Optometry of the Technical University of Catalonia (UPC, Terrassa, Spain). Only subjects with spectacle-corrected visual acuity of at least 6/6, spherical correction between ± 5.00 D and astigmatic correction less than or equal to 3.00 D were invited to participate. Participants had no history of ocular disease, surgery or pharmacological treatment. Contact lens wearers were instructed to cease lens wear for a complete day prior to the examination when using soft lenses and for three days, when using rigid lenses to avoid irregular changes in corneal shape. Only subjects with a pupil diameter of 4.0 mm or more in mesopic conditions (room illumination was 1.0 lux) were included in the study because a 4.0-mm pupil was later used to compute ocular aberrations. The study followed the tenets of the Declaration of Helsinki. All subjects gave written informed consent after receiving a written and verbal explanation of the nature of the study.

Twenty-nine right eyes of 29 participants were included in the study, with a mean and standard deviation (SD) in age of 26.5 ± 5.8 years (range: 18 to 52 years). The mean manifest spherical refractive error was −1.26 ± 1.93 D (−4.75 to +3.75 D) and the mean astigmatic refractive error was −0.76 ± 0.74 D (−3.00 to 0.00 D).

Examination protocol

Subjects underwent a standardised examination without cycloplegia to determine visual acuity, manifest refractive error and natural pupil diameter. Next, a sequence of aberrometric measurements, in mesopic conditions of the right eye of each participant was collected until nine measurements were obtained using both instruments (in a random order). Participants were uncorrected during the wavefront aberration measurement. The automatic mode of the KR-1 W instrument which enables centring, focusing and measuring without the operator's input was used.

Aberration data

Twenty-seven parameters, computed using a 4.0 mm pupil diameter, were used for the analysis: the individual Zernike coefficients from the second (C[2,m]) to the fifth order (C[5,m]), m being the angular frequency; the RMS of each order from the second ($RMS_{n=2}$) to the fifth order ($RMS_{n=5}$), the RMS of higher-order aberrations computed from the third to the fifth order (RMS_{HOA}), the total RMS computed from the second to the fifth order (RMS_{TOT}) and the objective refraction in the form of spherical equivalent (M) and Jackson cross-cylinder (J_0 and J_{45}). Aberrometric data were expressed in micrometres (μm) and refraction terms were expressed in dioptres (D).

Statistical analysis

Statistical analysis was performed using SPSS version 20 (IBM, Armonk, New York, USA) and Microsoft Office Excel 2007 (Microsoft, Redmond, Washington, USA). In all cases a 95% confidence interval was used, that is, a p-value of less than 0.05 was considered to be statistically significant.

The Kolmogorov–Smirnov test was used to evaluate the normality of all variables analysed. Bland and Altman analysis was used to study the agreement between the 27 parameters obtained from the two instruments.[17] The 95% limits of agreement (LoA) were calculated as 1.96 times the SD of the mean difference, and confidence limits were calculated for each LoA using Carkeet's exact method[18] considering the LoAs as a pair. A repeated measures MANOVA (multivariate analysis of variance), using the power vector terms (M, J_0 and J_{45}) as the dependent variables, was used to assess whether instrument type (that is, AOVA and KR-1 W) had statistically different refractive terms on average. Analogously, a repeated measures MANOVA using the 15 higher-order aberration terms, that is, the individual Zernike coefficients from the third to the fifth order, as the dependent variables was also performed. To examine each of the dependent variables individually, a paired sample t-test was used to determine statistically significant differences between the values provided by both aberrometers.

To determine the correlation between measurements of the two devices, bivariate correlations were also carried out and quantified using Pearson's correlation coefficient (r).

RESULTS

First, the achieved power was calculated using the G*Power software (v3.0.10) for statistical power analysis[19] using the mean of the differences and the mean standard deviation of the differences for all the Zernike coefficients. These values together with the significance level of 0.05, the two-tailed comparison and the sample size of 29 gave a power of 0.88, which is fairly good for the purpose of the study.

The Kolmogorov–Smirnov test showed that all data were normally distributed ($p > 0.05$). The descriptive data (mean, SD) are shown in Table 1. The mean Zernike coefficients and RMS parameters provided by both devices are shown in Figure 1. As expected, the largest Zernike coefficient mean value was obtained for the defocus term C(2,0) since all patients were uncorrected during examination.

Figure 2 shows the Bland and Altman plots for the objective refractive power vectors (M, J_0 and J_{45}) and the Zernike coefficients C(4,0), C(3,−1), C(3,1). Very few outliers in the data sets can be observed and the plots do not show any recognisable pattern, that is, differences do not systematically vary over the range of measurements, which indicates a good agreement between devices for these terms. Figure 3 illustrates some correlations obtained for the objective refraction (M, J_0 and J_{45}) and the Zernike coefficients C(4,0), C(3,−1), C(3,1).

The repeated measures MANOVA using the power vector (M, J_0 and J_{45}) terms as the dependent variables showed a statistically significant difference ($F_{3,26} = 8.18$, $p < 0.01$, Wilk's Lambda = 0.52). Similarly, the repeated measures MANOVA showed also a significant difference between instruments when considering the higher-order aberrations coefficients together ($F_{15,14} = 3.93$, $p < 0.01$, Wilk's Lambda = 0.19).

The examination of each of the dependent variables using a paired sample t-test to compare both aberrometers is shown in Table 1. No significant differences between instruments were found for the majority of parameters linked to individual Zernike coefficients; however, statistically significant differences were obtained for coefficients C(2,0), C (3,−1) and C(4,0), power vectors M and J_{45} and all RMS values. In addition to the paired sample t-test, Table 1 shows Pearson's correlation coefficients for both instruments. Statistically significant correlations ($p < 0.05$) were observed for most variables analysed except for the following parameters: C(4,−2), C(5,−5), C(5,1), C(5,5) and $RMS_{n=5}$; however, the mean differences between the AOVA and the KR-1 W for these coefficients were very small (Table 2), and clinically insignificant. In general, the Pearson's correlation coefficients

	AOVA		KR-1 W		Paired t-test	Pearson's correlation	
	Mean	SD	Mean	SD	p	r	p
Zernike coefficients (μm)							
C(2,−2)	0.050	0.150	0.074	0.151	0.060	0.941	<0.001*
C(2,0)	0.965	1.079	0.775	1.016	<0.001*	0.993	<0.001*
C(2,2)	−0.018	0.233	−0.033	0.228	0.104	0.972	<0.001*
C(3,−3)	−0.023	0.048	−0.036	0.043	0.139	0.825	<0.001*
C(3,−1)	0.006	0.042	−0.010	0.048	0.004*	0.834	<0.001*
C(3,1)	0.001	0.048	−0.004	0.047	0.734	0.874	<0.001*
C(3,3)	0.008	0.031	0.006	0.030	0.551	0.764	<0.001*
C(4,−4)	0.002	0.021	0.002	0.012	0.493	0.541	0.002*
C(4,−2)	0.001	0.011	−0.002	0.001	0.253	0.263	0.167
C(4,0)	0.033	0.026	0.013	0.025	0.001*	0.575	0.001*
C(4,2)	0.008	0.033	0.000	0.015	0.249	0.600	0.001*
C(4,4)	0.002	0.025	0.002	0.017	0.458	0.562	0.001*
C(5,−5)	0.003	0.017	−0.000	0.008	0.191	0.183	0.341
C(5,−3)	0.009	0.016	0.005	0.008	0.182	0.584	0.001*
C(5,−1)	−0.002	0.013	0.001	0.001	0.869	0.430	0.020*
C(5,1)	0.001	0.014	0.002	0.006	0.417	0.364	0.053
C(5,3)	−0.001	0.013	−0.002	0.006	0.847	0.573	<.001*
C(5,5)	−0.002	0.017	−0.001	0.007	0.988	0.254	0.184
Root mean squares (μm)							
$RMS_{n=2}$	1.185	0.876	1.024	0.808	<0.001*	0.993	<0.001*
$RMS_{n=3}$	0.120	0.043	0.092	0.033	0.001*	0.492	0.005*
$RMS_{n=4}$	0.089	0.034	0.039	0.019	<0.001*	0.408	0.023*
$RMS_{n=5}$	0.068	0.033	0.025	0.007	<0.001*	0.057	0.761
RMS_{TOT}	1.205	0.871	1.035	0.803	<0.001*	0.993	<0.001*
RMS_{HOA}	0.171	0.060	0.106	0.036	<0.001*	0.379	0.035*
Objective refraction (D)							
M	−1.570	1.865	−1.419	1.850	<0.001*	0.995	<0.001*
J_0	0.047	0.305	0.041	0.293	0.671	0.964	<0.001*
J_{45}	−0.058	0.192	−0.092	0.192	0.042	0.901	<0.001*

*Statistically significant correlations, D: dioptres, μm: micrometres

Table 1. Mean values and standard deviations (SD) obtained with the AOVA and the KR-1 W aberrometers for the Zernike coefficients, the root mean square (RMS) of each order and the objective refraction (spherical equivalent, J_0 and J_{45}). p-values of the paired sample t-test and Pearson's correlation coefficients (r) and corresponding significance (p-values) between measurements of the AOVA and KR-1 W aberrometers are also shown.

decreased as the order of the Zernike coefficient increased. The same tendency was observed when analysing the RMS values, for which higher Pearson's correlation coefficients were obtained for lower-order values, whereas no correlation was observed for the fifth-order RMS.

Table 2 shows the mean differences ($mean_d$), the SD of the mean differences and the corresponding 95% LoA and exact LoA confidence limits between measurements from both instruments according to the Bland and Altman analysis. The mean differences obtained were very close to zero in all cases. The largest mean difference in absolute terms were found for the defocus coefficient C(2,0) (0.190 μm). This Zernike coefficient is the main contributor to the spherical refractive error expressed in dioptres and since the mean difference in spherical equivalent between devices was −0.15 D (below 0.25 D), it can be considered of limited clinical significance, although, as shown in the Bland and Altman plot (Figure 2A), the spherical equivalent difference can be greater than 0.25 D in some individuals.

DISCUSSION

This study explored the agreement of several parameters provided by two commercial aberrometers, the AOVA and the KR-1 W, both based on the Hartmann–Shack

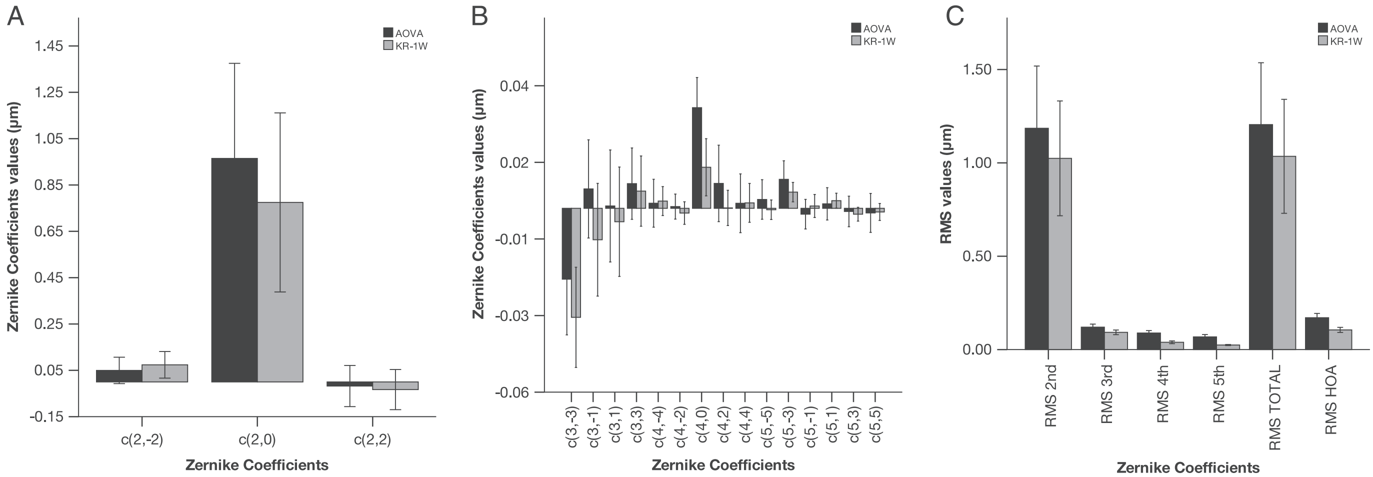

Figure 1. Mean value for the individual limits of agreement Zernike coefficients (A), individual higher-order aberration Zernike coefficients (B) and root mean square values (C) obtained with the AOVA and the KR-1 W aberrometers. µm: micrometres). Error bars represent the 95% confidence intervals.

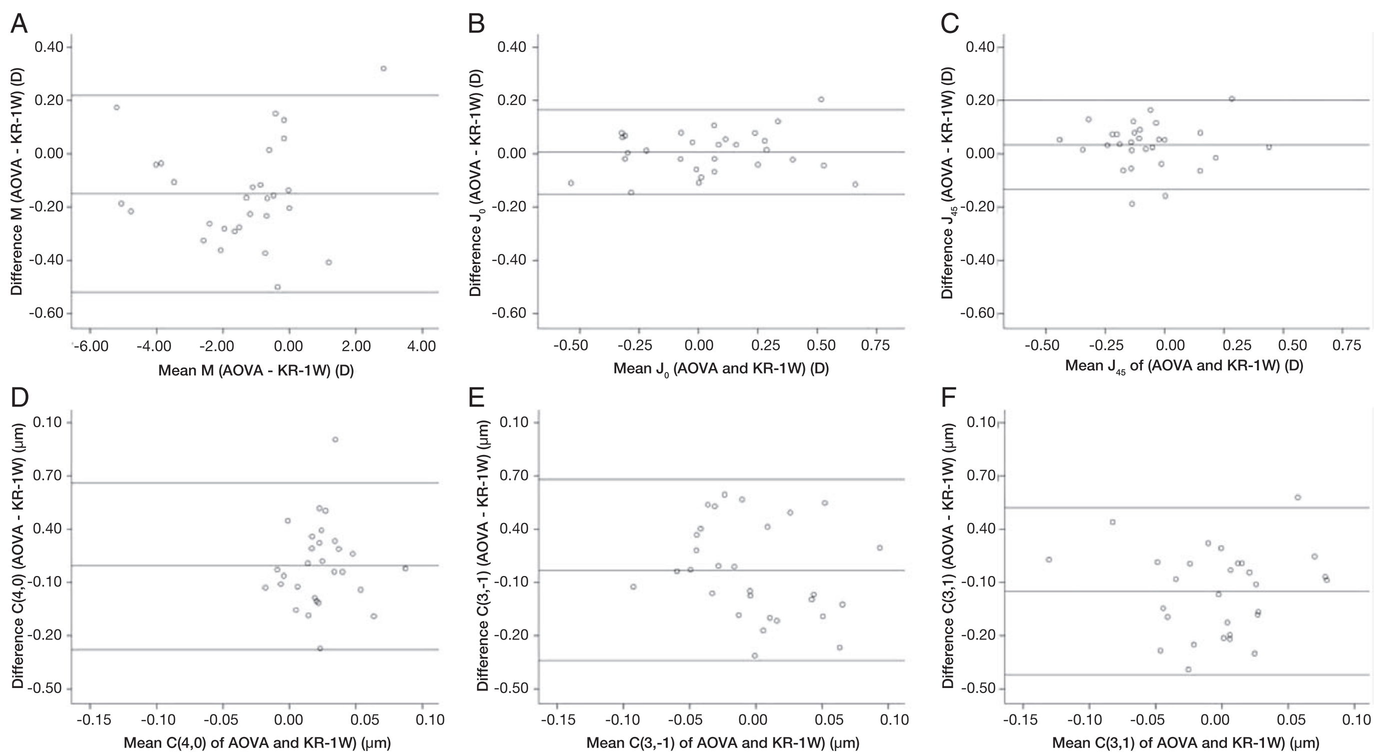

Figure 2. Bland and Altman plots showing the mean of the differences (mean$_d$) and the corresponding 95% limits of agreement (LoA) between the values obtained with the AOVA and KR-1 W aberrometers for the objective refraction spherical equivalent, J_0 and J_{45} (A, B, C, respectively) and for the individual Zernike coefficients C(4,0), C(3,−1), C(3,1) (D, E, F, respectively). D: dioptres, µm: micrometres.

technique. Our results showed good agreement between measurements from both instruments; however, no inferences regarding the trueness of the aberrometric measurements obtained can be drawn, as there is no gold standard.

In general, better agreement was observed for individual Zernike coefficients than for RMS values. The calculation of the RMS involves a non-linear transformation of the raw Zernike coefficients that makes them independent of the sign of the coefficient. As a consequence of the loss of information, the RMS might overestimate or underestimate the differences between measurements. Similar results were obtained by Rozema, Van Dyck and Tassignon,[7] when performing a comparison among several aberrometers.

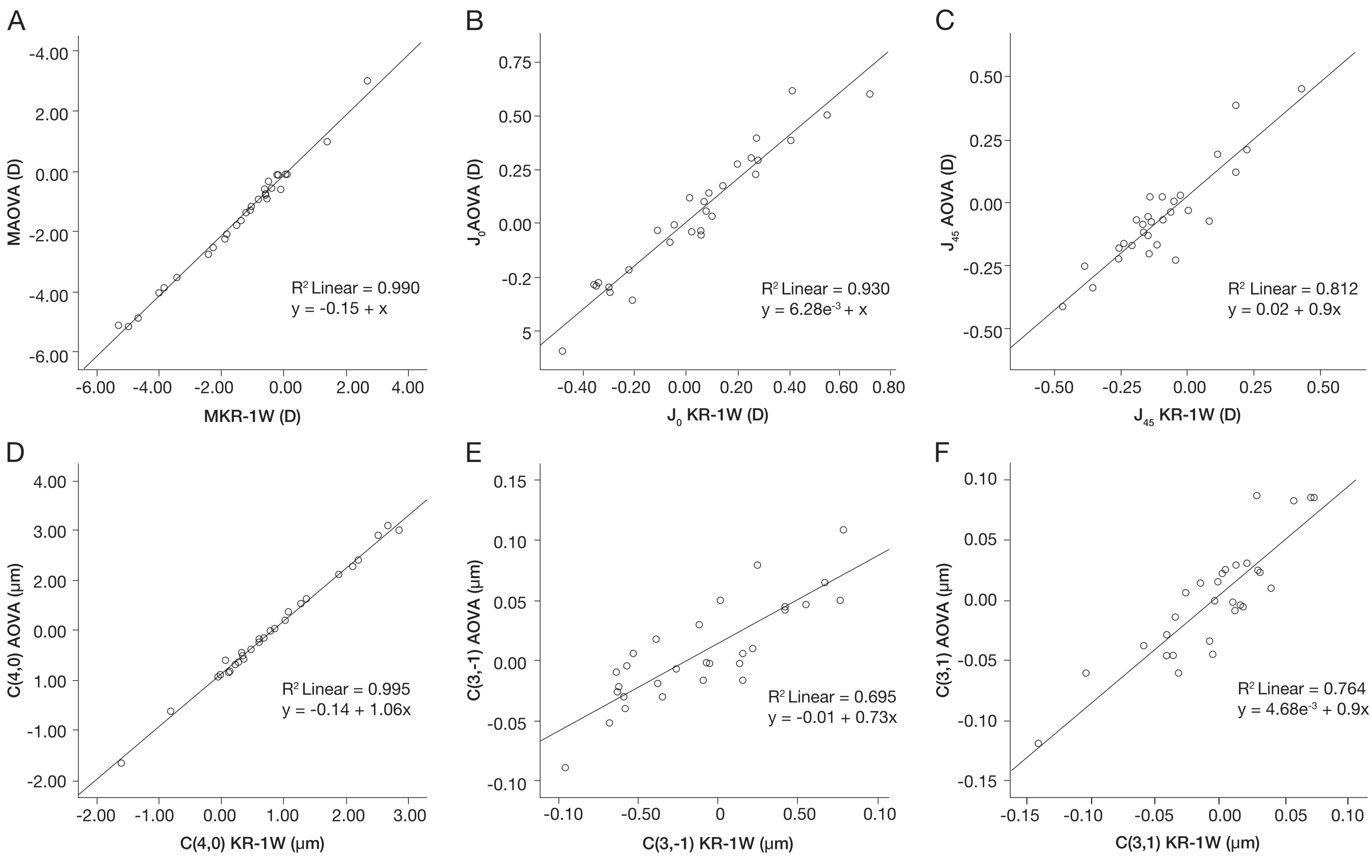

Figure 3. Correlation plots and regression coefficients between the AOVA and KR-1 W for the objective refraction spherical equivalent, J_0 and J_{45} (A, B, C, respectively) and the Zernike coefficients C(4,0), C(3,−1), C(3,1) (D, E, F, respectively). All correlations were significant ($p < 0.01$). D: dioptres, µm: micrometres.

The $mean_d$ between the RMS_{HOA} obtained with the AOVA and the RMS_{HOA} obtained with the KR-1 W provides an overall estimation of the error present, when comparing both devices. In our study this value (and SD) was 0.065 ± 0.063 µm, as can be seen in Table 2. It was computed as:

$$diffRMS_{HOA} = RMS_{HOA\,AOVA} - RMS_{HOA\,KR-1W} \quad (1)$$

in which the RMS_{HOA} of each device was calculated as:

$$RMS_{HOA} = \sqrt{\sum_{n=3}^{n}\sum_{-m}^{m}\left(C(n,m)\right)^2} \quad (2)$$

This estimation does not consider the individual HOA coefficient differences between both devices. Therefore, the following equation was used to take into account the mean RMS of the differences of each HOA coefficient ($RMS_{diffHOA}$).

$$RMS_{diffHOA} = \sqrt{\sum_{n=3}^{n}\sum_{-m}^{n}\left(C(n,m)_{AOVA} - C(n,m)_{KR-1W}\right)^2} \quad (3)$$

The mean $RMS_{diffHOA}$ was 0.077 ± 0.029 µm. In both cases the mean value and SD are fairly similar. When comparing these results with the magnitude of the measured RMS_{HOA} for each instrument, which are 0.171 and 0.106 µm for the AOVA and KR-1 W, respectively, it can be seen that both the $diffRMS_{HOA}$ and the $RMS_{diffHOA}$ are smaller. The differences between wavefront measurements in both devices differed by less than the magnitude of the measured wavefronts: 0.077 is about 73 and 45 per cent of the RMS_{HOA} for KR-1 W and AOVA, respectively. This suggests that for small wavefront errors (that is, eyes with low levels of aberrations, which was the case for most of the participants enrolled in this study) the overall agreement when measuring higher-order aberrations between devices might not be as good as expected.

In contrast, statistically significant differences in the defocus C(2,0), vertical coma C(3,−1) and spherical aberration C(4,0) coefficients were also obtained. These results seem to reflect a general trend observed when assessing the agreement between ocular aberrometric devices.[5,7,8,11]

Spherical aberration and defocus are of particular interest since their variability is linked to the change in the accommodative state of the eye.[5,9] Given that all patients underwent the examination without cycloplegia and although both instruments presented a target imaged at infinity, small changes in accommodation may play a role in the observed differences, as the

	$Mean_d$	SD	Lower LoA (CL)	Upper LoA (CL)
Zernike coefficients (μm)				
C(2,−2)	−0.024	0.050	−0.122 (−0.158;−0.103)	0.074 (0.055; 0.110)
C(2,0)	0.190	0.099	−0.004 (−0.076;−0.034)	0.384 (0.346; 0.456)
C(2,2)	0.015	0.055	−0.093 (−0.133;−0.072)	0.123 (0.102; 0.163)
C(3,−3)	0.012	0.028	−0.043 (−0.063;−0.032)	0.067 (0.056; 0.087)
C(3,−1)	0.017	0.026	−0.034 (−0.053;−0.024)	0.068 (0.058; 0.087)
C(3,1)	0.005	0.024	−0.042 (−0.059;−0.033)	0.052 (0.043; 0.069)
C(3,3)	0.002	0.021	−0.039 (−0.054;−0.031)	0.043 (0.035; 0.058)
C(4,−4)	0.001	0.018	−0.034 (−0.047;−0.027)	0.036 (0.029; 0.049)
C(4,−2)	0.002	0.013	−0.023 (−0.033;−0.019)	0.027 (0.023; 0.037)
C(4,0)	0.019	0.024	−0.028 (−0.045;−0.019)	0.066 (0.057; 0.083)
C(4,2)	0.008	0.027	−0.045 (−0.065;−0.035)	0.061 (0.019; 0.081)
C(4,4)	0.000	0.021	−0.041 (−0.056;−0.033)	0.041 (0.033; 0.056)
C(5,−5)	0.003	0.017	−0.030 (−0.043;−0.024)	0.036 (0.030; 0.049)
C(5,−3)	0.004	0.013	−0.021 (−0.031;−0.017)	0.029 (0.025; 0.039)
C(5,−1)	−0.003	0.012	−0.027 (−0.035;−0.022)	0.021 (0.016; 0.029)
C(5,1)	−0.001	0.013	−0.026 (−0.036;−0.022)	0.024 (0.020; 0.034)
C(5,3)	0.001	0.011	−0.021 (−0.029;−0.016)	0.023 (0.018; 0.031)
C(5,5)	0.000	0.017	−0.033 (−0.046;−0.027)	0.033 (0.027; 0.046)
Root mean squares (μm)				
$RMS_{n=2}$	0.161	0.124	−0.082 (−0.172;−0.035)	0.404 (0.357; 0.494)
$RMS_{n=3}$	0.028	0.043	−0.056 (−0.087;−0.040)	0.112 (0.096; 0.143)
$RMS_{n=4}$	0.050	0.035	−0.019 (−0.044;−0.005)	0.119 (0.105; 0.144)
$RMS_{n=5}$	0.044	0.034	−0.023 (−0.047;−0.010)	0.111 (0.098; 0.135)
RMS_{TOT}	0.170	0.123	−0.071 (−0.160;−0.024)	0.411 (0.364; 0.500)
RMS_{HOA}	0.065	0.063	−0.058 (−0.104;−0.035)	0.188 (0.165; 0.234)
Objective refraction (D)				
M	−0.150	0.188	−0.520 (−0.660;−0.447)	0.219 (0.147; 0.359)
J_0	0.006	0.081	−0.152 (−0.212;−0.121)	0.165 (0.134; 0.225)
J_{45}	0.034	0.085	−0.133 (−0.197;−0.101)	0.201 (0.168; 0.264)

Table 2. Mean differences ($mean_d$), mean standard deviation of the differences (SD) and 95% limits of agreement (LoA) between measurements of the AOVA and KR-1 W aberrometers. The 95% confidence limit (CL) for each LoA is also shown.

instruments were placed very close to the participants' eyes. Proximal accommodation induced by both devices could not be exactly the same.

In addition to changes in accommodation, some authors have suggested that an optical system with spherical aberration generates third-order coma as a linear function of pupil decentration.[11,20,21] Although in our study illumination was kept constant, differences in the targets of the analysed instruments could have induced small pupil displacements, which could contribute to the differences observed in coma.

On the other hand, factors related to the patients' variabilities could also affect agreement between devices. For instance, López-Miguel and colleagues[13] suggested that saccadic eye movements and tear-film instability can significantly reduce the reliability of higher-order aberration measurements. It has also been reported that instrument alignment can affect measurement.[7,13] Related to this, we must take into account that the KR-1 W has an automatic mode of centring that was used in all patients, whereas a manual alignment was used for the AOVA.

In addition, even though manufacturers make adjustments to minimise its influence, the wavelength of the light source included in each instrument might have had an impact on the results. Rodriguez and colleagues[14] suggest that the main difference found between aberrometers (they compared the Zywave, the Tracey and one experimental prototype) is due to longitudinal chromatic aberration caused by the use of different wavelengths. In particular, the authors found the sphere to differ by up to 0.7 D between infrared and green wavelengths. The AOVA operates at 808 nm and the KR-1 W in a range from 820 to 840 nm according to their specifications, which suggests that the difference in wavelength might have had only a small influence in this study.[6]

In conclusion, this study shows that the agreement (analysed over a 4.0 mm pupil) between the AOVA and KR-1 W instruments is good, although small but statistically significant differences in some Zernike coefficients and RMS parameters were found. Due to the lack of a gold standard or a universal calibrated test eye, it is important to highlight that deviations in measurements between aberrometers do not necessarily mean they are unreliable. On the other hand, patient and instrument variability could be reduced by increasing the number of measurements for each eye, as most instrument companies advise.

Future studies should compare wavefront analysers in different populations, such as in patients undergoing refractive surgery and in patients with corneal disorders, such as keratoconus, to determine the agreement between devices in eyes with higher levels of aberrations. In addition, comparison of devices under cycloplegic conditions would provide data free from the potential influence of accommodation and over larger pupil diameters.

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