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Aberrometry Repeatability and Agreement with Autorefraction

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Abstract

Significance—Commercially-available aberrometers are essential to clinical studies evaluating refractive error and image quality. The Discovery System is a promising clinical instrument that allows investigators to export aberration data for research and analysis purposes. An assessment of the Discovery System's performance is essential to the interpretation of the data obtained.

Purpose—To determine the between-visit repeatability of refractive error and higher-order aberration measurements with the Discovery System, and to examine between-instrument agreement of refractive error measurements with the Discovery System and Grand Seiko WAM-5500 open-field autorefractor.

Methods—Cycloplegic refractive error values from the Discovery System (over a 3-mm pupil) and the Grand Seiko autorefractor were converted to power vectors (M, J0, and J45) and averaged. Zernike coefficients were also calculated by the Discovery System over a 6-mm pupil through the 6th radial order. Between-visit repeatability and agreement were evaluated using Bland-Altman difference versus mean plots. T-tests compared each mean difference (bias) to zero and the 95% limits of agreement (LoA) were calculated.

Results—Twenty-five young adults with a mean ($\pm$ SD) cycloplegic spherical-equivalent refractive error of -2.91 ± 1.85 D (range: -6.96 to $+0.74$) were enrolled. There were no significant between-visit differences with the Discovery System for M, J0, J45, 3rd through 6th order RMS, HORMS, or spherical aberration (all $p > 0.30$), and repeatability for defocus and HORMS were ± 0.31 D and ± 0.095 μ m, respectively, for a 6-mm pupil. At a 3-mm pupil, the Discovery System on average measured slightly more positive values than the Grand Seiko for M (0.28 D), J0 (0.11 D), and J45 (0.12 D; all $p < 0.005$).

Conclusions—The Discovery System was very repeatable and would be an appropriate instrument to measure cycloplegic refractive error and higher-order aberration changes in adults. Small differences in refractive error were found between the Discovery System and Grand Seiko.

Keywords

between-visit repeatability; aberrometry; lower-order aberrations; higher-order aberrations; between-instrument agreement; Hartmann screen

Measurements of both lower-order and higher-order aberrations are critical in a wide range of clinical studies evaluating refractive error and image quality, such as studies of myopia

and keratoconus.^{1–5} Grand Seiko autorefractors (Grand Seiko Co., Hiroshima, Japan), also manufactured under the name Shin-Nippon, are frequently used in clinical studies to objectively measure refractive error because of their well-documented repeatability; however, the Grand Seiko autorefractor does not measure higher-order aberrations.^{6–12} Hartmann-Shack aberrometry has been widely used in clinical research over the last several decades.^{13, 14} The Complete Ophthalmic Analysis System (COAS; AMO Wavefront Sciences, Albuquerque, New Mexico), a commercial Hartmann-Shack aberrometer, has been widely used in clinical research to simultaneously measure both lower-order (refractive error) and higher-order aberrations. The repeatability of the COAS was documented and refractive error measurements had been validated against the Grand Seiko autorefractor; however, the COAS is no longer commercially available.^{15–18} There is a need for a commercially available aberrometer with accurate refraction measurements and known repeatability in clinical research. Having access to these data allows for more detailed analysis such as calculating metrics of image quality.

The Discovery System (Innovative Visual Systems, Elmhurst, Illinois) is a new commercially-available wavefront aberrometer. Unlike the COAS, which uses a Hartmann-Shack approach,^{13, 19} the Discovery System utilizes a Hartmann-screen design. This design does not utilize a lenslet array and has a high-dynamic range that eliminates the need to pre-correct defocus as is done by the COAS. The instrument is capable of calculating Zernike coefficients up to the 10th radial order over a range of pupil sizes. The purpose of this study is to assess the between-visit repeatability of refractive error (lower-order) and higher-order aberration measurements made with the Discovery System, and to examine the between-instrument agreement of refractive error measurements between the Discovery System and the Grand Seiko WAM-5500 open-field autorefractor.

METHODS

Adults between the ages of 18 and 39 were recruited to participate in two study visits separated by no more than 14 days. The study protocol was approved by the University of Houston Committee for the Protection of Human Subjects and followed the guidelines of the Declaration of Helsinki. Study subjects were provided a written informed consent document that they signed prior to enrollment. All subjects had no history of ocular disease, ocular trauma, ocular surgery, or systemic diseases that could cause refractive error variation (e.g., diabetes). Rigid gas permeable contact lens wearers were excluded and soft contact lens wearers were instructed to wear glasses on the days of their study visits.

Measurements

Five consecutive cycloplegic measurements of the right eye were made with the Discovery System at two separate visits (Visit 1 and Visit 2). Subjects fixated the red fixation spot within the instrument. The Discovery System captures a single measurement with each button press, and each measurement was made after instructing the subject to blink twice and open their eye. Measurements were taken at the same time of day (± 1 hour) during the two visits and all subjects were asked to present to visits with no contact lenses on. Ten consecutive cycloplegic measurements of the right eye were also made using the Grand

Seiko WAM-5500 at Visit 2. Instrument order at the second visit was randomized. Measurements were made under cycloplegia (1% tropicamide) using an established cycloplegia protocol frequently used in both adult and pediatric clinical research.^{20, 21} The Discovery System does not fog the internal target, making cycloplegia important to ensure relaxed accommodation. Measurements began 30 minutes after the first of two drops of 1% tropicamide that were separated by five minutes. All subjects wore a patch over the left eye to ensure accurate fixation by the right eye during measurements.

Prior to each measurement, the examiner inspected the subject's alignment to ensure each subject was positioned with their chin on the chin rest and their forehead against the forehead rest. The measurement axis of the Discovery System was aligned with the right eye's line of sight by instructing the subject to fixate on the instrument's internal fixation light. Before each measurement, subjects were instructed to blink twice and then hold their eye open. Between each measurement, the examiner re-evaluated each subject's alignment. For measurements with the Grand Seiko WAM-5500, subjects fixated a red LED spot of light on the wall directly in front of them.

Data Analysis

Zernike coefficients were calculated by the Discovery System over a 6-mm pupil diameter through the 6th radial order. The measurements were averaged and exported for further analysis. Refractive error values were exported from the Discovery System (sphere, cylinder, and axis) and the Grand Seiko autorefractor. The Discovery System utilized only the second-order aberration values to compute the refractive error displayed. For the Discovery System, refractive error values were obtained for the 6-mm diameter over which all Zernike coefficients were calculated and for a 3-mm pupil diameter to allow for comparable conditions when comparing to refractive error measurements made by the Grand Seiko autorefractor's 2.3-mm measurement beam diameter.²² A 3-mm pupil is the smallest diameter for which the Discovery System displays refractive error data (sphere, cylinder, and axis). All refractive error values were converted to power vectors (M , J_0 , and J_{45}) using previously described methods and averaged.²³ The root mean square (RMS) wavefront error was calculated for third-, fourth-, fifth-, sixth-order terms, and total higher-order RMS (HORMS) was calculated using the 3rd through 6th order Zernike terms.

Statistical analyses were performed using STATA 12 (Stata Corp., College Station, TX). Between-visit repeatability and between-instrument agreement were evaluated using Bland-Altman difference versus mean plots.²⁴ Differences between the two visits for M , J_0 , J_{45} , third-order RMS, fourth-order RMS, fifth-order RMS, sixth-order RMS, HORMS, vertical trefoil (C_3^{-3}), vertical coma (C_3^{-1}), horizontal coma (C_3^1), oblique trefoil (C_3^3), oblique secondary astigmatism (C_4^{-2}), spherical aberration (C_4^0), and vertical secondary astigmatism (C_4^2) were calculated. Differences between the two instruments for M , J_0 , and J_{45} were also calculated. The mean of the differences describes the bias. A t-test ($\alpha = 0.05$) was used to compare each mean difference to zero. When a Shapiro-Wilk test indicated lack of normality, a non-parametric sign test was used instead. A Pearson correlation or, when a non-parametric test was appropriate, a Spearman correlation was used to assess the relationship between the differences and means for each plot. The 95% limits of agreement

(LoA) were calculated for each comparison as the mean difference $\pm 1.96 \times$ standard deviation of the differences. Exact 95% confidence intervals for the upper and lower limits of agreement were also calculated.²⁵

Sample Size Calculation

When designing this study, the only previous repeatability study using the Discovery System reported the repeatability of internal aberrations (whole eye aberrations minus corneal aberrations) as opposed to whole eye aberrations.²⁶ The largest between-visit standard deviation reported for internal eye refraction components (M, J₀, and J₄₅) was for defocus using a 4.5 mm pupil (0.24 D = 0.177 μ m). Assuming a two-sided alpha of 0.05 and 80% power, a sample size of 8 subjects was needed to detect a 0.25 D difference in M, J₀, and J₄₅ (the greatest contributors of whole eye aberrations). We also repeated the calculation after inflating the standard deviation by 50% to 0.36 D to account for any potential increased variability in our study, which resulted in a sample size of 17 subjects. A total of 25 subjects were enrolled in this study.

RESULTS

Twenty-five adults between the ages of 22 and 29 completed both visits. The median time between Visit 1 and Visit 2 was 5 days (range: 1 to 14 days). The mean ($\pm$ SD) age at Visit 1 was 23.4 ± 1.7 years. The mean ($\pm$ SD) cycloplegic spherical-equivalent refractive error and cylinder as measured by the Grand Seiko WAM-5500 at Visit 2 were -2.91 ± 1.85 D (range: -6.96 to $+0.74$) and -0.54 ± 0.35 D (range: -1.38 to 0.00), respectively. Of the 25 subjects in the study, 18 (72%) were female.

Between-Visit Repeatability

The bias (mean difference between Visit 1 and Visit 2), repeatability of power vector components (M, J₀, J₄₅) measured with the Discovery System, and confidence intervals for the limits of agreement for a 6-mm and 3-mm pupil are shown in Table 1. There were no significant differences between visits for M, J₀, or J₄₅ (all $p > 0.71$). The difference versus mean plots for a 6-mm pupil for M, J₀, J₄₅ are shown in Figure 1. The 95% LoA (repeatability) of measurements of J₀ and J₄₅ were both less than a quarter of a diopter while the repeatability of the defocus term (M) was ± 0.31 D for a 6-mm pupil. For a 3-mm pupil, similar results were obtained for J₀ and J₄₅. The repeatability of the defocus (M) increased to ± 0.35 D. The bias, repeatability of the higher-order aberration measurements, and confidence intervals for the limits of agreement for a 6-mm pupil are shown in Table 2. The bias was not significantly different from zero for HORMS, third-, fourth-, fifth-, sixth-order RMS, vertical coma, horizontal coma, oblique secondary astigmatism, spherical aberration, or vertical secondary astigmatism (all $p > 0.25$). The Discovery System measured on average $+0.022$ microns more vertical trefoil and -0.014 microns less oblique trefoil at the first visit compared to the second visit (both $p < 0.05$); while statistically significant, these biases are very small clinically. Difference versus mean plots for higher-order aberrations are shown in Figure 2. Between-visit repeatability of HORMS was ± 0.095 μ m. For the spherical aberration term and the other RMS values calculated by radial order, repeatability ranged from ± 0.029 to ± 0.106 μ m.

Between-Instrument Agreement

The bias, agreement of cycloplegic refractive error components (M , J_0 , J_{45}) between the Discovery System and Grand Seiko WAM-5500, and confidence intervals for the limits of agreement for a 6-mm and 3-mm pupil are shown in Table 3. For a 6-mm pupil, the analysis did not find any evidence indicating that there was systematic bias for measurement of defocus (M) between instruments ($p = 0.45$). For J_0 and J_{45} , the Discovery System on average measured 0.14 and 0.13 D higher than the Grand Seiko at a 6-mm pupil, respectively (both $p < 0.001$). However, for a 3-mm pupil which is more similar to the measurement beam diameter of the Grand Seiko, the Discovery System on average measured more positive values than the Grand Seiko for defocus (0.28 D), J_0 (0.11 D) and J_{45} (0.12 D; all $p < 0.005$). The difference versus mean plots for refractive error measurements for a 3-mm pupil are shown in Figure 3. The 95% LoA between instruments was greater for defocus than for the astigmatism terms.

DISCUSSION

Determining the repeatability of instruments to be used in clinical research under normal conditions to establish its validity in terms of measurement limitations is essential. Because of the increasing public health risk associated with myopia, many clinical research studies are evaluating possible therapeutic devices for slowing the rate of myopia progression in children.^{1, 3, 27} These studies require the longitudinal assessment of refractive error changes, which necessitates clear knowledge of instrument validity and repeatability in children. Additionally, aberrometry measurements are commonly made when there is an interest in image quality, such as in studies evaluating refractive error, contact lenses for myopia control, and corneal diseases such as keratoconus. Higher-order aberrations are significantly increased in patients with keratoconus and degrade the retinal image in these patients.^{2, 28} Studies utilizing aberrometry are being done to design custom treatments for keratoconus.²⁹ Objective measurements of image quality are useful in a variety of clinical research applications but require a robust instrument that is research-friendly and repeatable.

Refractive Error Repeatability and Agreement

Several studies have evaluated the repeatability of non-cycloplegic refractive error measurements using Grand Seiko autorefractors and have found the repeatability to be between ± 0.50 D to ± 0.86 D.^{6–8, 10–12} As expected, better repeatability has been reported under cycloplegic conditions (range: ± 0.12 D to ± 0.48 D). In our study, the repeatability of the Discovery System (± 0.34 D) was found to be comparable to the repeatability of the Grand Seiko autorefractor under cycloplegic conditions in adult subjects.^{6, 9, 12}

The Grand Seiko obtains measurements using a 2.3-mm measurement beam. In contrast, the minimum pupil diameter for which the Discovery System displays refractive error data (sphere, cylinder, and axis) is 3 mm. Therefore, an analysis of measurement agreement between the two instruments was conducted for both a 6-mm pupil and a 3-mm pupil. With a 3-mm pupil, all power vector components of refractive error measurements (M , J_0 , and J_{45}) were statistically different between the two instruments, with the Discovery System measuring +0.28 D more defocus than the Grand Seiko. By contrast, this study failed to find

any evidence of bias for spherical-equivalent defocus (M) between the Discovery System across a 6-mm pupil and Grand Seiko. While both instruments are very repeatable, the between-instrument 95% LoA of ± 0.77 D indicate that the use of the Discovery System interchangeably with the Grand Seiko for defocus measurements is not advisable. The bias between the two instruments for J_0 and J_{45} astigmatism was statistically significant with the Discovery System measuring slightly more of each across a 3-mm pupil (0.11 D and 0.12 D, respectively). Although these differences are clinically small, the differences indicate that the astigmatic components are not interchangeable between the instruments. That being said, the repeatability of astigmatism measurements on the Discovery System across visits was very good (J_0 : ± 0.13 D; J_{45} : ± 0.14 D).

Repeatability of Higher-order Aberrations

In addition to lower-order aberrations (refractive error), higher-order aberrations also influence retinal image quality. Although not correctable with traditional ophthalmic corrections like glasses or contact lenses, higher-order aberrations can have a meaningful influence on vision, especially in conditions with elevated higher-order aberrations such as keratoconus.^{30–33} In patients treated with laser-assisted in situ keratomileusis (LASIK), common post-treatment visual complaints are glare and halos, which are correlated with increases in post-treatment higher-order aberrations.^{34–38} Optical corrections currently being studied for myopia control like orthokeratology increase higher-order aberrations;³⁹ therefore, measuring aberrations with these treatments is important when evaluating their influence on image quality. Repeatable clinical instruments for measuring changes in higher-order aberrations due to refractive procedures and contact lenses are important.

The Discovery System showed very repeatable results for measures of higher-order aberrations (HORMS 95% LoA = ± 0.095 μ m) that were similar to a previous study that assessed the repeatability of HORMS measurements in an adult population made at different visits on the same day using the COAS aberrometer (95% LoA = ± 0.132 μ m).⁴⁰ Differences in HORMS that lie outside the 95% LoA have a 95% probability of being a true change in HORMS between visits and 5% probability of being due to instrument measurement error. Therefore, a difference in HORMS between visits that is greater than 0.095 microns will have a 95% probability of being a true change in HORMS.

In evaluating the Discovery System's ability to detect a change in both normal and abnormal populations, we reviewed the normal aberration levels in different populations reported in the literature. A study by Salmon and van de Pol established normal-eye RMS values.⁴¹ The mean values for HORMS, third-, fourth-, fifth-, sixth-order RMS, and spherical aberration in our study were all within one standard deviation of their study. The mean ($\pm$ SD) HORMS in our study was 0.431 ± 0.123 microns compared to the mean HORMS of 0.327 ± 0.130 microns found in their study of subjects between the ages of 20 and 70.⁴¹ The mean HORMS in our study was also within one standard deviation of the HORMS reported by Karimian et al. (0.35 ± 0.12 microns) in a study of normal myopic subjects with an age range (18–43 years) that more closely resembles our subjects.⁴² In contrast, eyes with abnormal corneal conditions like keratoconus have higher than average HORMS. A study in patients with keratoconus fitted with a spherical-equivalent scleral lens measured between

0.20 to 0.90 microns of residual HORMS. Ten out of the 14 eyes measured had residual HORMS values greater than 0.4 microns.²⁹ Changes in HORMS after procedures such as orthokeratology are generally on the order of more than 0.15 to 0.20 microns.^{39, 43} Additionally, in a normal population, the average change in HORMS seen with age from 20 year olds to 50 years olds is 0.109 microns for a 6mm pupil.⁴⁴ Based on the repeatability found in this study, the Discovery System is capable of detecting 0.10 micron changes in HORMS in adult eyes under cycloplegia.

The Discovery System was also repeatable when HORMS was decomposed to assess each radial order individually. One previous study found good repeatability for measurements of spherical aberration using the Discovery System (intra-session 95% LoA = $\pm 0.083 \mu\text{m}$; between-session 95% LoA = $\pm 0.051 \mu\text{m}$); however, that study evaluated the repeatability of internal aberrations.²⁶ In our study, we evaluated total ocular aberrations between measurements made on different days and found the between-visit repeatability to be similar (95% LoA = $\pm 0.070 \mu\text{m}$).

To put RMS wavefront error into more clinically meaningful terms, RMS can be converted from microns to equivalent diopters of defocus using a previously published formula.⁴⁵ The repeatability for the HORMS ($\pm 0.095 \mu\text{m}$) is equivalent to $\pm 0.07 \text{ D}$ of defocus, and the repeatability for the spherical aberration term ($\pm 0.070 \mu\text{m}$) is equivalent to $\pm 0.05 \text{ D}$ of defocus, both of which are clinically small.

A potential limitation of our study is that we did not investigate the repeatability of the instrument under non-cycloplegic conditions. The purpose of the study was to assess the repeatability of the instrument; therefore, controlling the potential impact of accommodation was essential. Repeatability would likely be worse under non-cycloplegic conditions, which would be consistent with repeatability studies of autorefraction.¹² Another limitation is that repeatability was assessed in a normal population. It is possible that the repeatability of the instrument could be different in highly-aberrated eyes or in children. However, a review of studies assessing the repeatability of autorefraction in children using instruments with a similar point-and-click capture method to the Discovery suggests similar repeatability to an adult population.^{46, 47} A study evaluating repeatability of the Shin Nippon SRW-5000 in children conducted by Chat et al. found differences in repeatability between children that were cyclopleged versus those that were not (Defocus 95% LoA cyclopleged: $\pm 0.35 \text{ D}$ vs non-cyclopleged: $\pm 0.45 \text{ D}$). The study suggests that the cycloplegic state of the subject is a critical variable that affects repeatability.⁴⁶ The repeatability in non-cyclopleged children in their study is well within the range of repeatability found across studies in non-cyclopleged adults using the Grand Seiko/Shin Nippon autorefractor (95% LoA range: ± 0.43 to $\pm 0.86 \text{ D}$).^{7, 8, 10, 48} Additionally, it is possible that repeatability could be influenced by highly-aberrated eyes or when measuring refractive errors outside the range of those included in the current study. Overall, although studies of autorefraction do not show differences in repeatability between children and adults, future studies assessing the Discovery System's validity should focus on assessing the instrument's repeatability in highly-aberrated eyes and in children.

In conclusion, the Discovery System was found to be very repeatable. The instrument allows users to measure ocular aberrations and export the full Zernike data, making it a promising research instrument. Though, on average, there were minimal differences in refractive error measured between the Grand Seiko and Discovery, the 95% LoA for refractive error measurements between instruments suggest that one should not use refractive error values interchangeably between these instruments. The good repeatability of the Discovery System when measuring both refractive error and higher-order aberrations indicates that it would be an appropriate instrument to track changes in refractive error and visual quality in longitudinal studies in adults.

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Figure 1. Between-visit repeatability of refractive error measurements using the Discovery System. Difference versus mean plots for repeated measurements of central spherical-equivalent defocus (A), J_0 (B), J_{45} (C) measured at two separate visits for a 6-mm pupil. The solid line represents the mean difference between the two visits (bias). The dashed line represents the 95% limits of agreement.

Figure 2.

Between-visit repeatability of higher-order aberration measurements (6-mm pupil diameter) using the Discovery System. Difference versus mean plots for repeated measurements of HORMS (A), third-order RMS (B), fourth-order RMS (C), fifth-order RMS (D), sixth-order RMS (E), and spherical aberration (F) measured at two separate visits. The solid line represents the mean difference between the two visits (bias). The dashed line represents the 95% limits of agreement.

Figure 3.

Refractive error agreement between the Discovery System (for a 3-mm pupil) and the Grand Seiko WAM-5500. Difference versus mean plots for repeated measurements of central spherical-equivalent defocus (A), J_0 (B), J_{45} (C) measured with each instrument. The solid line represents the mean difference between the two instruments (bias). The dashed line represents the 95% limits of agreement.

Table 1

Between-visit repeatability of refractive error measurements (diopters) for the Discovery System

	Bias *	Repeatability **	Upper LoA (CI) ***	Lower LoA (CI) ***
6mm pupil				
M	-0.01 ± 0.16	± 0.31	0.29 (0.42,0.23)	$-0.32 (-0.26, -0.45)$
J₀	0.00 ± 0.07	± 0.13	0.12 (0.18,0.10)	$-0.13 (-0.11, -0.19)$
J₄₅	0.00 ± 0.07	± 0.14	0.14 (0.20,0.11)	$-0.13 (-0.10, -0.19)$
3mm pupil				
M	-0.02 ± 0.04	± 0.35	0.32 (0.08,0.03)	$-0.37 (-0.08, -0.12)$
J₀	-0.01 ± -0.09	± 0.18	0.17 (0.24,0.13)	$-0.18 (-0.15, -0.26)$
J₄₅	0.02 ± 0.06	± 0.12	0.14 (0.20,0.12)	$-0.10 (-0.08, -0.15)$

* Mean ($\pm$ SD) difference between two visits (Visit 1 – Visit 2)

** $1.96 \times$ SD of differences between visits (Limits of Agreement = LoA)

*** 95% confidence interval (CI) is in parenthesis for the upper and the lower 95% LoA

Table 2

Between-visit repeatability of higher-order aberration measurements (microns) for the Discovery System

	Bias [*]	Repeatability ^{**}	Upper LoA (CI) ^{***}	Lower LoA (CI) ^{***}
6mm				
HORMS	0.002 ± 0.049	± 0.095	0.098 (0.138,0.078)	-0.093 (-0.073, -0.133)
Third-Order RMS	0.002 ± 0.054	± 0.106	0.108 (0.152,0.086)	-0.104 (-0.082, -0.149)
Fourth-Order RMS	0.006 ± 0.033	± 0.064	0.070 (0.097,0.057)	-0.057 (-0.044, -0.084)
Fifth-Order RMS	0.003 ± 0.016	± 0.032	0.035 (0.048,0.028)	-0.029 (-0.022, -0.042)
Sixth-Order RMS	0.003 ± 0.015	± 0.029	0.032 (0.044,0.026)	-0.026 (-0.020, -0.038)
C₃⁻³ (Vertical Trefoil)	0.022 ± 0.045	± 0.088	0.110 (0.147,0.092)	-0.065 (-0.047, -0.102)
C₃⁻¹ (Vertical Coma)	-0.007 ± 0.074	± 0.146	0.140 (0.201,0.109)	-0.153 (-0.123, -0.215)
C₃¹ (Horizontal Coma)	-0.002 ± 0.056	± 0.109	0.108 (0.154,0.085)	-0.111 (-0.088, -0.157)
C₃³ (Oblique Trefoil)	-0.014 ± 0.028	± 0.056	0.042 (0.065,0.030)	-0.070 (-0.058, -0.093)
C₄⁻² (Oblique 2° Astig.)	0.002 ± 0.019	± 0.038	0.040 (0.056,0.032)	-0.036 (-0.028, -0.052)
C₄⁰ (Spherical Aberration)	0.005 ± 0.036	± 0.070	0.074 (0.104,0.060)	-0.065 (-0.050, -0.094)
C₄² (Vertical 2° Astig.)	-0.007 ± 0.028	± 0.054	0.048 (0.071,0.036)	-0.061 (-0.050, -0.084)

* Mean (±SD) difference between two visits (Visit 1 – Visit 2)

** 1.96 × SD of differences between visits (Limits of Agreement = LoA)

*** 95% confidence interval (CI) is in parenthesis for the upper and the lower 95% LoA

Table 3

Refractive error agreement (diopters) between the Discovery System and the Grand Seiko WAM-5500

	Bias[*]	Repeatability^{**}	Upper LoA (CI)^{***}	Lower LoA (CI)^{***}
6mm pupil				
M	0.07 ± 0.43	± 0.85	0.91 (1.27,0.74)	−0.78 (−0.60, −1.14)
J₀	0.14 ± 0.16	± 0.31	0.46 (0.59,0.39)	−0.17 (−0.10, −0.30)
J₄₅	0.13 ± 0.15	± 0.29	0.41 (0.54,0.36)	−0.16 (−0.10, −0.28)
3mm pupil				
M	0.28 ± 0.39	± 0.77	1.05 (1.37,0.89)	−0.49 (−0.33, −0.82)
J₀	0.11 ± 0.17	± 0.34	0.45 (0.60,0.38)	−0.23 (−0.16, −0.37)
J₄₅	0.12 ± 0.15	± 0.30	0.42 (0.55,0.35)	−0.19 (−0.12, −0.31)

^{*} Mean (±SD) difference between the two instruments (Discovery System - Grand Seiko)

^{**} $1.96 \times \text{SD}$ of differences between the two instruments (Limits of Agreement = LoA)

^{***} 95% confidence interval (CI) is in parenthesis for the upper and the lower 95% LoA