Original Article

Comparison of higher order wavefront aberrations with four aberrometers

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Purpose: To evaluate the agreement of selected higher order aberration measurements between aberrometers based on three different wavefront technologies. **Methods:** Twenty-three eyes of 23 participants were compared between Zywave, OPD-Scan III, and iDesign aberrometers, for total ocular aberrations. Participants were between 19 and 69 years of age, and exclusion criteria were previous ocular surgery or trauma, contact lens wear within the preceding 2 weeks, and ocular or systemic disease. Corneal aberrations were compared between the OPD-Scan III and GALILEI™ G2 aberrometers. Zernike coefficients of vertical and oblique trefoil, vertical and horizontal coma, and spherical aberration were analyzed in R software. **Results:** In all, 276 scans were captured in total, with a male-to-female ratio of 11:12. Total ocular vertical coma [mean difference (MD) = 0.026 µm, $P < 0.005$], vertical trefoil (MD = 0.033 µm, $P < 0.05$), and spherical aberration (MD = 0.022 µm, $P < 0.05$) differed significantly between the iDesign and OPD-Scan III. Differences in total vertical (MD = 0.072 µm, $P < 0.05$) and oblique trefoil (MD = 0.058 µm, $P < 0.05$) were demonstrated between the Zywave and OPD-Scan III, and spherical aberration (MD = 0.030 µm, $P < 0.005$) between iDesign and Zywave. iDesign corneal horizontal coma (MD = 0.025 µm, $P < 0.05$) and spherical aberration (MD = 0.043 µm, $P < 0.005$) measurements were significantly different between the GALILEI™ G2 and the OPD-Scan III. **Conclusion:** Zywave, iDesign, and OPD-Scan III, and GALILEI™ G2 and OPD-Scan III may be used interchangeably for their total ocular and corneal wavefront functions, respectively; however, care must be taken if using these devices for guiding ablation or monitoring corneal disease.

Key words: Higher order aberrations, LASIK, wavefront aberrometry

Access this article online
Website: www.ijo.in
DOI: 10.4103/ijo.IJO_1464_18
Quick Response Code:

Wavefront-sensing devices rapidly and objectively measure combinations of total ocular, corneal, and internal wavefront aberrations, which quantify the aberrations in the eye's complete refractive media, cornea, and lens, respectively. Zernike polynomials quantify these optical aberrations and allow them to be compared between machines. Previous studies have noted that lower order aberrations are more comparable than higher order aberrations in evaluations of different machine pairs. Higher order aberrations can be significantly different between devices at the third order, which includes coma and trefoil,[1] perhaps due to the different mathematical systems used to calculate them.[2] Furthermore, lower order aberrations can also differ substantially between devices, including Hartmann–Shack device pairs, and Hartmann–Shack and automatic retinoscopy device pairs.[3]

Higher order aberrations are clinically relevant as some dysphotopsias including night halos and glare have been associated with high amounts of higher order aberrations (HOA).[4] Correction of aberrations beyond simple sphere and cylinder will also theoretically increase retinal image resolution and contrast.[5] This would allow patients to see with finer and higher contrast, with particular benefits to pilots flying in low-light conditions now that the safety of refractive surgery has been proven in extreme visual environments.[6]

Four wavefront aberrometers commonly used in refractive surgery are the Zywave (Bausch and Lomb, Rochester, NY, USA), OPD-Scan III (Nidek Technologies, Gamagori, Japan), iDesign (Abbott Medical Optics, Inc., Santa Ana, CA, USA), and GALILEI™ G2 (Zeimer Ophthalmic Systems AG, Port, Switzerland). These devices are based on different measurement principles; Zywave and iDesign use Hartmann–Shack,[7,8] while OPD-Scan III uses automatic retinoscopy,[9] and GALILEI™ G2 calculates HOA with its dual-Scheimpflug and Placido topography system.[10] To the best of our knowledge, this study is the first to assess the agreement between these devices.

There is currently no gold standard modality for the measurement of ocular aberrations;[2] therefore, it is important that the agreement of clinical aberrometers is regularly assessed to ensure wavefront-guided (WFG) LASIK is consistent between centers using different aberrometers. The degree of agreement of these devices may provide useful information for clinicians in measuring, correcting, and monitoring HOAs after refractive and cataract surgery. It is necessary to compare agreement between these devices in a clinical setting. This study also aims to evaluate the clinical implication of any significant

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Manuscript received: 21.09.18; Revision accepted: 17.02.19

Cite this article as: Cook WH, McKelvie J, Wallace HB, Misra SL. Comparison of higher order wavefront aberrations with four aberrometers. Indian J Ophthalmol 2019;67:1030-5.

interdevice differences, which offers additional information to clinicians and patients considering surgery.

Methods

This study was conducted in accordance with the Declaration of Helsinki, and formal approval was obtained from the Health and Disability Ethics Committee of New Zealand (16/CEN/132). Twenty-five participants were recruited from the population at the study institution to participate in this prospective, comparative study over a 2-week period. All participants provided informed consent prior to study participation, and exclusion criteria included previous ocular surgery or trauma, contact lens wear within the preceding 2 weeks, ocular or systemic disease that may affect the cornea or lens, or less than 18 years of age. This study excluded patients with ocular histories as we intended to assess normal eyes without more than refractive error. This excluded two patients, one less than 18 years of age and one with early cataract changes of the lens. Participants were included if they were 18 years of age, did not meet any exclusion criteria, and gave informed consent. Twenty-three participants were therefore included in the study.

A single trained investigator obtained three sets of measurements per device for each patient, spread over three different visits. Uniocular measurements were taken to avoid the confounding effects of intereye HOA correlation.[11,12] Zywave and GALILEI™ G2 were used at a university eye clinic and public hospital, respectively. iDesign and OPD-Scan III were located at a private Auckland eye clinic, and a random number generator was used to determine the device scanning order. All measurements with Zywave, OPD-Scan III, iDesign, and GALILEI™ G2 aberrometers were obtained under scotopic conditions. All measurements were acquired according to the manufacturer's instructions, and participants were requested to blink 2 s prior to measurement acquisition. Zywave is an early Hartmann–Shack aberrometer, which measures 75 data points through the pupil and calculates up to five orders of Zernike coefficients.[7] iDesign is another Hartmann–Shack sensor that gathers more than 1,250 data points from up to a 7.0-mm pupil.[8] OPD-Scan III is a five-in-one device with topographer, keratometer, pupillometer, and wavefront aberrometer functions. Wavefront aberrations are calculated by automatic retinoscopy, and the resulting refractive power map can be separated into total ocular, corneal, and internal components for mesopic, photopic, and manual pupil sizes.[9] GALILEI™ G2 is a topographer and wavefront aberrometer that uses a combination of two rotating Scheimpflug cameras and a Placido disc to examine the anterior segment and calculate HOA.[10]

At the time of measurement, pupil sizes were calculated by each device, and all participants had at least 4 mm of pupil size at each measurement for analysis to be performed based on this size. Three devices were able to scale physiological pupil size to a central 4.0-mm zone by reducing the number of sensors used to measure aberrations. Zywave aberrometer does not possess this function, so previously described pupil scaling[13] was implemented in R version 3.3.0 (2016-05-03). Zernike coefficients of vertical and horizontal coma, vertical and oblique trefoil, and spherical aberration were calculated by each device's software systems. Statistical analysis was performed using R Studio. For aberrometers reporting total ocular aberrations, Zywave, iDesign, and OPD-Scan III, Zernike coefficients of vertical and oblique trefoil, vertical and horizontal coma, and spherical aberration were compared with Bland–Altman analysis for comparison among the three aberrometers. Corneal aberrations from the two aberrometers reporting corneal Zernike coefficients, the OPD-Scan III and GALILEI™ G2, were also compared with Bland–Altman analysis. Bland–Altman plots were used to visualize these comparisons by plotting the difference between measurements against their mean along with additional lines representing the limits of agreement. The 95% limits of agreement [mean difference (MD) ±1.96 × standard deviation] define the range of differences between measurements from the two devices.

Results

Twenty-three eyes of 23 participants were enrolled for this study (48% male and 52% female; 22 right eyes and 1 left eye). The mean age was 27.2 ± 17.1 years (range, 19–69 years). All GALILEI™ G2 and OPD-Scan III measurements were within the minimum acceptable standard as reported by the internal software of those aberrometers. No iDesign or Zywave scans were deemed unacceptable by their visually represented quality scores.

In total, 276 images were captured from 23 eyes with three measurements obtained for four devices and averaged into one result by the Zywave and OPD-Scan III devices. The right eye was scanned first for each participant, and the left eye was scanned if an acceptable measurement could not be obtained after three attempts. Each device provides varying amounts of data when exported, but participant codes, pupil sizes, and Zernike polynomials for vertical and horizontal coma, vertical and oblique trefoil, and spherical aberration were collected for analysis.

Table 1 shows the results of total ocular aberration analysis, and Bland–Altman plots demonstrate the agreement between devices [Fig. 1]. iDesign and Zywave presented statistically congruent measurements of both components of coma and trefoil, but measurements of spherical aberration differed significantly ($P < 0.005$). iDesign and OPD-Scan III were congruent across horizontal coma and oblique trefoil, but differed in measurements of vertical coma ($P < 0.005$), vertical trefoil ($P < 0.05$), and spherical aberration ($P < 0.05$). OPD-Scan III and Zywave were congruent across both coma components and primary spherical aberration, but differed in measuring both components of trefoil ($P < 0.05$). Bland–Altman plots demonstrated that for measurements of both coma components and vertical trefoil, iDesign and OPD-Scan III demonstrated the narrowest limits of agreement, while for oblique trefoil and primary spherical aberration, iDesign and Zywave demonstrated the narrowest limits of agreement.

Table 2 shows the results of corneal aberration analysis, and Bland–Altman plots demonstrate the agreement between GALILEI™ and OPD-Scan III [Fig. 2]. Measurements of vertical coma and both components of trefoil were statistically congruent between devices. Horizontal coma and primary spherical aberration demonstrated the narrowest limits of agreement despite differing significantly ($P < 0.05$ and $P < 0.005$, respectively), while oblique trefoil was noted to have the widest limits of agreement.

Discussion

This study assessed the comparability of four wavefront aberrometers' measurements of selected HOAs and to postulate their interchangeability in clinical practice. The

Table 1: Bland-Altman analysis of total ocular aberrations from different aberrometers

Aberration	Mean Diff.	P	LoA
Vertical coma			
iDesign - OPD-Scan III	0.026	**0.0001**	−0.025 to+0.078
iDesign - Zywave	0.034	0.152	−0.184 to+0.252
OPD-Scan III - Zywave	0.008	0.687	−0.182 to+0.199
Horizontal coma			
iDesign - OPD-Scan III	0.002	0.768	−0.067 to+0.071
iDesign - Zywave	−0.001	0.969	−0.204 to+0.202
OPD-Scan III - Zywave	−0.003	0.879	−0.188 to+0.182
Vertical trefoil			
iDesign - OPD-Scan III	0.033	**0.010**	−0.078 to+0.143
iDesign - Zywave	−0.039	0.118	−0.266 to+0.188
OPD-Scan III - Zywave	−0.072	**0.033**	−0.370 to+0.255
Oblique trefoil			
iDesign - OPD-Scan III	−0.040	0.067	−0.233 to+0.154
iDesign - Zywave	0.019	0.124	−0.091 to+0.129
OPD-Scan III - Zywave	0.058	**0.008**	−0.129 to+0.245
Primary spherical			
iDesign - OPD-Scan III	0.022	**0.040**	−0.074 to+0.118
iDesign - Zywave	0.030	**0.0008**	−0.042 to+0.102
OPD-Scan III - Zywave	0.008	0.551	−0.109 to+0.124

Diff.: mean difference (μm); LoA: limits of agreement (μm)

Table 2: Bland-Altman analysis of corneal aberrations from GALILEI™ G2 and OPD-Scan III

Aberration	Mean Diff.	P	LoA
Vertical coma	0.018	0.136	−0.091 to+0.127
Horizontal coma	−0.025	**0.008**	−0.106 to+0.055
Vertical trefoil	−0.017	0.194	−0.133 to+0.100
Oblique trefoil	−0.022	0.302	−0.219 to+0.175
Primary spherical	−0.043	**0.00008**	−0.094 to+0.008

Diff.: mean difference (μm); LoA: limits of agreement (μm)

results demonstrate that device pairs are variably similar in their measurement functions and have limits of agreement that may have visually significant outcomes.

iDesign and Zywave were the most comparable device pair for total ocular HOA, with statistically similar measurements of both components of coma and trefoil. This device pair also demonstrated the narrowest limits of agreement for oblique trefoil and spherical aberration, despite the latter differing significantly between devices. Considering the HOAs themselves, measurements of coma were comparable between Zywave, OPD-Scan III, and iDesign, with the latter two differing in only the vertical component of coma [Table 1]. Trefoil and spherical aberrations were significantly different between multiple device pairs, which is comparable to the findings of another study assessing similar machines;[3] however, it should be noted that iDesign and Zywave agreed on trefoil in this study. Another study reported spherical aberration and horizontal coma to be significantly different between the devices they assessed with wide limits of agreement,[2] while vertical coma and trefoil were comparable. In contrast, only iDesign and Zywave had comparable vertical trefoil measurements, while horizontal coma was comparable across all device pairs and demonstrated narrower limits of agreement in this study.

Most measurements of corneal HOA were comparable between OPD-Scan III and GALILEI™ G2, with differences noted in horizontal coma and spherical aberration. Measurements of spherical aberration demonstrated narrower limits of agreement than any other HOA [Fig. 2]. A similar theme was noted in total ocular measurements of spherical aberration, which were significantly different between iDesign, and both OPD-Scan III and Zywave devices [Fig. 1]. Reportedly, there is good comparability between corneal measurements across most,[10] if not all HOAs,[3] which may be due to topography-assisted computations that calculate corneal aberration from total ocular HOA and corneal structure.[3,10] This is complemented in this study with iDesign and Zywave demonstrating the best total ocular device pairing, suggesting Hartmann–Shack devices may be best for evaluating total ocular HOA.

Bland–Altman analysis does not address the aim of determining interchangeably in clinical practice, and so quantitative analysis of the visual effect of given amount of aberration is required to make sense of the significant differences. Just-noticeable differences (JND) reveal the importance of small variations in HOA on subjective visual perception. A JND is a quantitative measure of aberration that causes a subjective change in visual quality.[14] Interdevice HOA differences that exceed their corresponding JND are clinically significant. Spherical aberration has a JND of 0.036 and 0.070 μm in two studies using side-by-side simulated images with 6.0-mm pupils and adaptive optics with 5.0-mm pupils, respectively.[15,16] The smaller JND was exceeded by the MD between OPD-Scan III and GALILEI™ G2 (MD = 0.043 μm) and was approaching being exceeded by iDesign and Zywave (0.030 μm) for 4.0-mm pupils in this study. The 95% limits of agreement between OPD-Scan III and GALILEI™ G2 (−0.094 to 0.008 μm), and iDesign and Zywave (−0.042 to 0.102 μm) exceeded the larger and smaller JND, respectively. These studies did not make a distinction between the different components of coma a trefoil and so these aberrations cannot be evaluated with their corresponding JND. Interdevice differences may produce clinically different visual outcomes if a patient was to undergo refractive surgery based on one or either of these devices and should be considered by clinicians with access to multiple devices.

Clinical differences may be demonstrated with WFG LASIK, the gold standard of laser refractive surgery.[17] This procedure uses wavefront aberrometry to individualize ablation as opposed to the older photorefractive keratectomy and conventional LASIK procedures that do not correct for HOA and so do not rely on wavefront aberrometry. Successful WFG LASIK then relies on good wavefront data, uncomplicated surgery, and predictively managing postoperative changes in aberration to ensure long-term patient satisfaction.[18] To this aim, WFG LASIK enhances the optical quality of the patient's retinal image by minimizing the amount of surgically induced HOA. Rather than using unique aberrometry data, wavefront-optimized LASIK also aims to minimize surgically induced HOA using population-based ablation profiles. However, this method induces more postoperative HOA than WFG LASIK in patients with >0.3 μm of preoperative total HOA.[19] Thus, WFG LASIK should be guided by aberrometry data from a single device for consistent visual performance postoperatively.

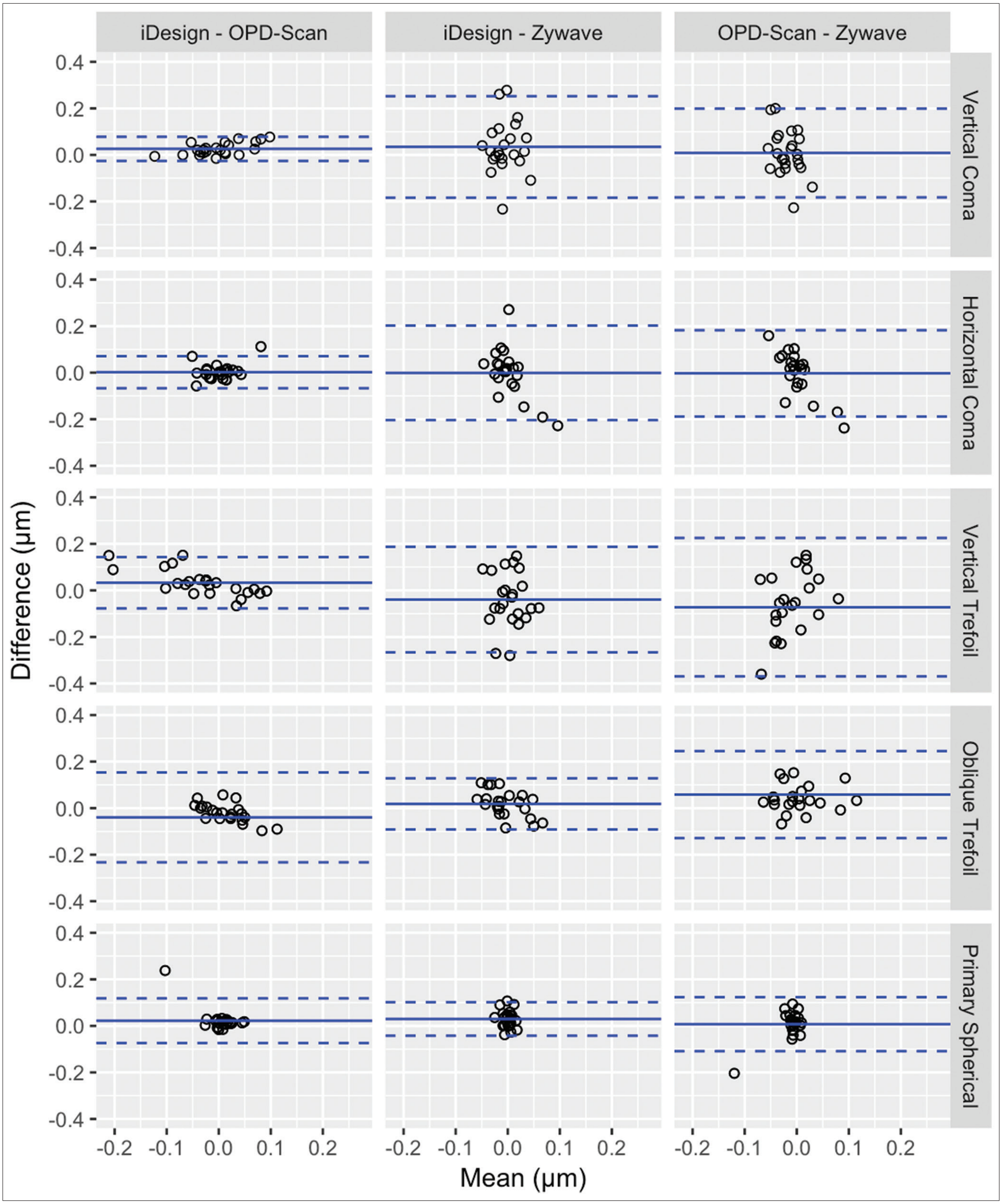

Figure 1: Agreement of selected ocular higher order aberration measurements (in micrometers) obtained by three wavefront aberrometers: Zywave, iDesign, and OPD-Scan III (OPD-Scan). Central line = mean of the difference between the two methods; peripheral lines = 95% limits of agreement

Perfect visual acuity does not correspond to a perfect retinal image.[20] While lower order aberrations account for more than 90% of the eye's total aberration, all HOAs will worsen image quality even when those of a lower order have been corrected.[21] HOAs are especially troublesome after conventional LASIK or when the pupil is large, which is why they are commonly associated with night vision difficulties. Coma and spherical aberration have the greatest effect on contrast sensitivity in this manner.[22]

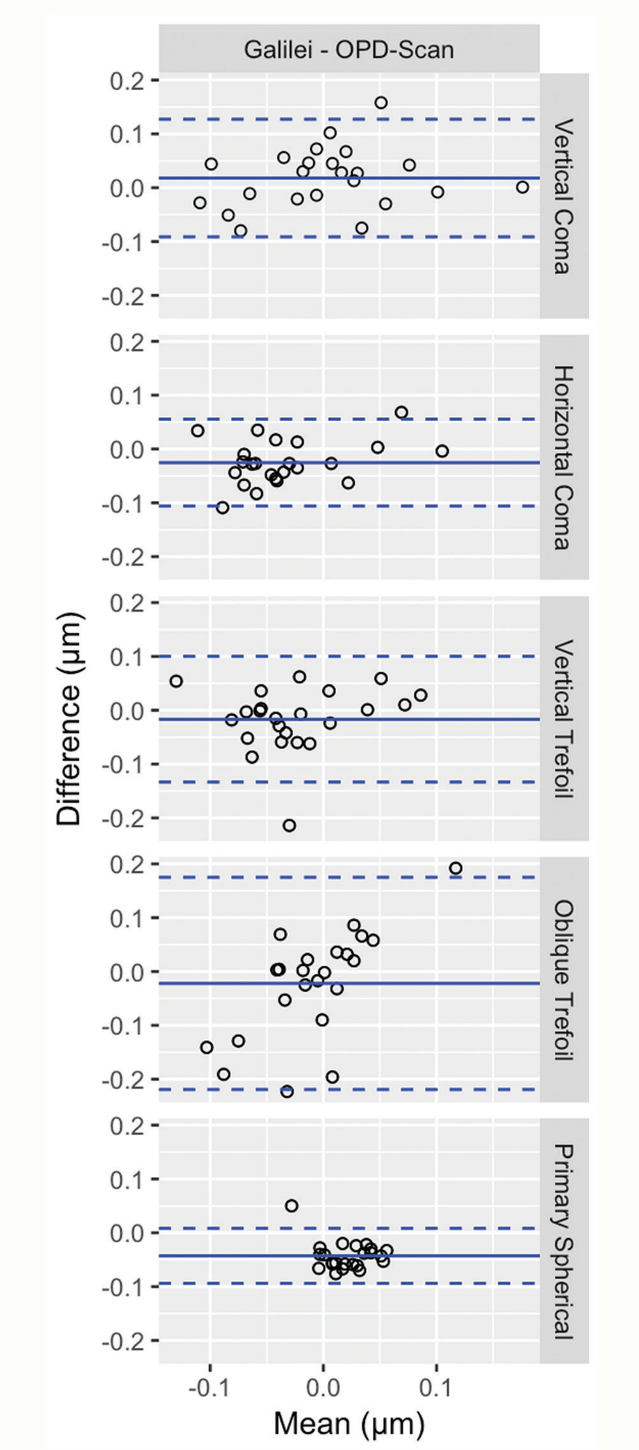

Figure 2: Agreement of selected corneal higher order aberration measurements (in micrometers) obtained by two wavefront aberrometers using Bland–Altman plots: GALILEI™ G2 (GALILEI) and OPD-Scan III (OPD-Scan). Central line = mean of the difference between the two methods; peripheral lines = 95% limits of agreement

The latter tends to be positively induced in conventional LASIK, which induces positive and negative spherical aberrations after myopic and hyperopic ablation, respectively, whereas WFG LASIK reduces the amount of surgically induced HOA.[18,23-26] As WFG LASIK offers comparatively better postoperative visual performance than conventional surgery, it is difficult to elucidate whether small measurement differences between aberrometers will make a visually significant difference.[27] However, as technology advances, a clinician's ability to minimize HOA will demand more accurate aberrometry, and differences between aberrometers could compromise patient outcomes or affect accurate measurements of operatively induced spherical aberration and reduced coma after corneal ring implantation for keratoconus.[28] However, it is important to note that a patient's visual symptoms should be a primary concern when planning refractive surgery, rather than relying solely on HOA measurement.

The difficulty in ensuring consistent pupil centration worsens the repeatability of HOA measurements.[26,29,30] All devices evaluated in this study require some degree of manual pupil and corneal alignment prior to measurement acquisition. Each of the devices in this study provides a reliability score of each measurement. Use of these functions is essential to ensure a fair comparison with high-quality data from the devices as they are used in clinical practice. Reliable and comparable measurements of submicrometer HOAs may be limited by the aberrometers used, patient variability, or a combination of both. Participants in this study were examined over three appointments at different times of day and may have been performing different visual tasks before each scan. Tear film quality during HOA measurements could have been influenced by these preceding activities. The experimental method in this study ensured that all participants blinked before each measurement and the aberrometers reduced accommodation with image fogging; however, tear film instability and accommodation are known sources of HOA measurement error and are difficult to avoid entirely.[31,32]

It is worth noting that despite the Zywave pairings demonstrating good statistical congruence, the limits of agreement tended to exceed those of iDesign and OPD-Scan III pairing. Perhaps an explanation of this result, repeatability of each device is a relevant contributing factor to the pair's agreement,[17] and although not studied here, it should be considered in future evaluations of these devices for complete comparability analysis. Automatic averaging of the three measurements taken with Zywave and OPD-Scan III precluded evaluating repeatability with the examinations conducted in this study; however, previous studies have assessed the reproducibility of these devices.[7-10,33,34] In clinical practice, the importance of adhering to each manufacturer's recommendations regarding the number of aberrometry measurements is required for successful laser refractive surgery outcomes.[1]

Conclusion

This study has reported significant differences between most devices, some of which exceed the JND of the respective HOA, and thus may compromise the visual outcome of WFG LASIK. The importance of this study is to highlight where different devices are likely to differ and by how much, as using this information clinicians are able to better understand the results and limitations of each, and factor this into treatment decisions. Corneal aberrations were more comparable than total ocular aberrations, reflecting the utility of a topographer in the aberrometry workstation. While coma compared well across different devices, spherical aberration did not and was prone to recording significant outlying measurements. This should encourage clinicians to exercise caution when using these devices interchangeably, especially prior to laser refractive surgery or when patients with corneal disease relocate nationally or internationally and need high-quality monitoring of their progressive condition.

Acknowledgements

The authors wish to acknowledge Professor Charles McGhee for his mentorship and support of this research, and Dr. Trevor Gray and Nick Mathew at Eye Institute for the use of iDesign and OPD-Scan III devices.

Clinical Trial Reg. No.

Registered with Australian New Zealand Clinical Trial Registry, registration number ACTRN12616001593426.

Financial support and sponsorship

School of Medicine Foundation, Faculty of Medical and Health Sciences, The University of Auckland.

Conflicts of interest

There are no conflicts of interest.

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