

Repeatability of i.Profiler for Measuring Wavefront Aberrations in Healthy Eyes

Xuan Liao

Affiliated Hospital of North Sichuan Medical College

Mei-Jie Wang

Affiliated Hospital of North Sichuan Medical College

Qing-Qing Tan (✉ tqq0720@126.com)

North Sichuan Medical College <https://orcid.org/0000-0002-3858-0528>

Chang-Jun Lan

Affiliated Hospital of North Sichuan Medical College <https://orcid.org/0000-0002-1040-9622>

Research Article

Keywords: i.Profiler, Repeatability, Corneal aberration, Ocular aberration, Pupil diameter

Posted Date: April 1st, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-178818/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at International Ophthalmology on April 5th, 2022. See the published version at <https://doi.org/10.1007/s10792-022-02300-x>.

Abstract

Purpose

To evaluate the repeatability of wavefront aberration measurements and the correlation between corneal aberration and pupil size in normal eyes using a wavefront-based autorefractor (i.Profiler^{Plus}; Carl Zeiss Vision, Germany).

Methods

A prospective cross-sectional study. Wavefront aberrations, including SA (Z_4^0), coma (Z_3^{-1} , Z_3^1), trefoil (Z_3^{-3} , Z_3^3) and total higher-order aberrations (tHOA), were measured at different pupil diameters. The repeatability was evaluated using one-way ANOVA method, and statistical indicators including within-subject standard deviation (S_w), test-retest repeatability (TRT), and intra-class correlation coefficient (ICC). The correlations between corneal aberrations and pupil sizes were evaluated by Pearson correlation analysis.

Results

A total of 96 healthy young volunteers were enrolled. Corneal and ocular higher-order aberrations (HOA) measured by i.Profiler showed $S_w < 0.01 \mu\text{m}$, $TRT < 0.10 \mu\text{m}$, $ICC > 0.90$. There was a linear positive correlation between the corneal HOA and pupil size. The correlation coefficient between SA and tHOA was the largest ($r = 0.996$, $P < 0.001$).

Conclusions

The measurements of wavefront aberrations by i.Profiler are highly repeatable. Corneal HOA is significantly dependent on pupil size. SA is the most influential aberration for visual quality.

Key Messages

- The i.Profiler (Carl Zeiss Vision, Germany) is a novel device that comprehensively assesses visual quality by measuring both lower- and higher-order aberrations at a wide pupil range (2 to 7mm).
- Excellent repeatability of the i.Profiler has been shown in measuring refraction, however, repeatability data of higher-order aberration measurements are lacking.
- This study shows the repeatability of the i.Profiler in measuring wavefront aberrations and the correlation between corneal aberration and pupil size.

Introduction

Aberration of the human eyes is the main factor degrading retinal image and visual performance and has been shown to be crucial in many ophthalmic practices, e.g., wavefront-optimized refractive surgery and irregular astigmatism diagnosis[1, 2]. It is believed that aberrations also play a role in the development and control of refractive error and eye growth by influencing the retinal image quality and ocular accommodation response, and the relative focal plane of different regions of the entrance pupil[3]. Since the magnitude and type of ocular wavefront aberration vary significantly between individuals, the comprehensive and accurate measurement of both lower-order aberrations (LOAs) and higher-order aberrations (HOAs) is a prerequisite for evaluating refractive error and image quality[3]. However, conventional autorefractors can only quantify LOAs (defocus and astigmatism) but not HOAs (spherical aberration, coma, trefoil, etc.); also, it measures the overall refractive power of the eye confined to a small central area of the pupil. Instead, wavefront autorefractors can provide not only a reasonable refractive accuracy but also a total aberration in wavefront pattern and local variations in refractive power of the entire visual system, and therefore begins to be popularized in clinical applications[4, 5].

The i.Profiler^{Plus} (Carl Zeiss Vision, Germany) is a novel wavefront aberrometer autorefractor based on Hartmann-Shack microlens array sensor. Due to the distorted wavefront, namely the aberrated wavefront generated by an eye, the central ray of the infrared laser beam tends to tilt as it passes through each lenslet in the array. Through the analysis of these tilts, the refractive error was calculated and the optical aberrations were quantified by Zernike coefficients up to the 7th radial order over a range of pupil size. Lebow et al.[6] compared the noncycloplegic subjective refractive output of i.Profiler^{Plus} with that of Canon RK-F2, a ray deflecting principle autorefractor, suggesting that both instruments can provide equivalent spherocylindrical refractive data. Previous study has demonstrated the repeatability of cycloplegic and noncycloplegic measurements for i.Profiler^{Plus} in terms of the autorefraction function[7]. However, very few data are available on the repeatability of this instrument with respect to wavefront aberration measurements. The purpose of this study provides a reference for clinical applications by evaluating the repeatability of i.Profiler^{Plus} on the ocular and corneal HOA measurements, and the correlations between HOAs and pupil diameters for the first time in normal eyes.

Methods

Subjects

In this prospective study, young volunteers with normal eyes were consecutively recruited at the Affiliated Hospital of North Sichuan Medical College from May to July 2018. Inclusion criteria were healthy eyes with a corrected distance visual acuity $\geq 20/20$. Exclusive criteria consisted of ocular pathology or systemic disease with ocular symptoms, a recent history of contact lens wearing or dry eye, and a previous history of intraocular and corneal surgery or trauma. The targeted total sample size is 96 with 3 repeated measurements and within 10% confidence level[8]. All participants were provided a written informed consent document to be signed prior to enrollment. All procedures were conducted on the basis

of the approval of the hospital's Ethics Committee [2018ER(A)036] and followed the guidelines of Helsinki Declaration.

Procedures

Routine examinations included distance uncorrected visual acuity (UCVA), best corrected visual acuity (BCVA), manifest refraction, non-contact tonometry, slit-lamp biomicroscopy and ophthalmoscopy. A well-trained examiner was involved in the experimental procedure. The i.Profiler device was used to obtain the following measurements: the corneal and ocular vertical coma (Z_3^{-1}), horizontal coma (Z_3^1), vertical trefoil (Z_3^{-3}), oblique trefoil (Z_3^3), spherical aberration abbreviated SA (Z_4^0) and total high-order aberration (tHOA). Pupil was dilated to more than 7mm using a mixture of 0.5% tropicamide and 0.5% phenylephrine (Mydrin P, Santen Pharmaceutical, Osaka, Japan). Only the right eye was used for the analysis because data from both eyes is similar in a healthy population. The subjects placed their heads on the chin rest and fixated on the test mark during the measurement period. For each subject, three consecutive mydriatic measurements were made with the i.Profiler under repeatable conditions. For each measurement, the subjects blinked to allow an optically smooth tear film to spread over the cornea. The instrument automatically aligned the pupil center with the optical axis of the device to ensure that the spot of the measuring laser hits the macular fovea accurately.

Statistical analysis

Statistical analyses were performed using the statistics software SPSS 25.0 (IBM Corp., USA). The demographic characteristics were summarized using descriptive statistics. The normality of data was evaluated by means of the Kolmogorov-Smirnov test ($P > 0.05$). The results of the parameters were reported as means and standard deviations (SD). The repeatability of the measurements was described in terms of within-subject standard deviation (S_w), and repeatability limits or test-retest repeatability (TRT). One-way analysis of variance (ANOVA) was performed to determine S_w . Considering the 95% confidence interval (C) of S_w , the repeatability limit was calculated as $1.96\sqrt{2}\times S_w$ or $2.77\times S_w$, which provides an estimate of the limits within which 95% of measurements should be [8]. The intra-class correlation coefficient (ICC) of test-retest reliability was also calculated, which represents the consistency of measurement [9]. The correlation between corneal aberrations and pupil sizes was evaluated by Pearson correlation analysis. A P value less than 0.05 was considered to denote statistical significance.

Results

Ninety-six eyes of 96 healthy subjects (48% males and 52% females) were included in the study. Their mean age was 21 ± 1.9 years (range 18 to 28 years), the average spherical refraction was -1.40 ± 1.00 D (range 0.00 to -3.00 D), and the average cylindrical refraction was -0.50 ± 0.50 D (range 0.00 to -1.00 D). All subjects' pupils can be dilated to 7 mm or larger. No participants were withdrawn or dropped out.

Repeatability of corneal high order aberration

The i.Profiler provided highly repeatable measurements for corneal high order aberration ($ICC > 0.9$, $S_w < 0.01 \mu\text{m}$, $TRT < 0.1 \mu\text{m}$). Table 1 summarizes the mean values and repeatability metrics for corneal high order aberration at 2 mm ~ 7 mm pupil diameter. $ICCs$ of corneal Z_3^{-1} and Z_3^1 at 6mm pupil diameter were 1.0, showing an excellent consistency of measurements. The TRT values were all less than $0.02 \mu\text{m}$ with one exception of $0.22 \mu\text{m}$ at 6 mm pupil diameter SA (Z_4^0); a lower TRT value represents a higher repeatability. At 3 mm pupil diameter, the values of corneal tHOA and SA were $0.050 \pm 0.022 \mu\text{m}$ and $0.016 \pm 0.007 \mu\text{m}$, respectively; at 5 mm pupil diameter, $0.220 \pm 0.059 \mu\text{m}$ and $0.116 \pm 0.031 \mu\text{m}$, respectively.

Table 1
Repeatability of corneal high order aberration

Parameter	Diameter (mm)	Mean \pm SD (μm)	ICC	(95%CI)	S_w (μm)	TRT (μm)
tHOA	2	0.020 \pm 0.013	0.929	0.946 ~ 0.960	0.002	0.006
	3	0.050 \pm 0.022	0.998	0.997 ~ 0.998	0.001	0.003
	4	0.120 \pm 0.048	0.999	0.999 ~ 0.999	0.001	0.003
	5	0.220 \pm 0.059	0.963	0.949 ~ 0.974	0.001	0.003
	6	0.390 \pm 0.100	0.999	0.999 ~ 0.999	0.003	0.008
	7	0.690 \pm 0.070	0.999	0.999 ~ 1.000	0.003	0.008
	Z_4^0	2	0.004 \pm 0.002	0.994	0.993 ~ 0.997	0.001
3		0.016 \pm 0.007	0.992	0.988 ~ 0.994	0.002	0.006
4		0.049 \pm 0.016	0.992	0.988 ~ 0.994	0.001	0.003
5		0.116 \pm 0.031	0.995	0.983 ~ 0.996	0.002	0.006
6		0.270 \pm 0.040	0.977	0.968 ~ 0.984	0.005	0.015
7		0.543 \pm 0.082	0.994	0.991 ~ 0.996	0.008	0.022
Z_3^{-3}		2	0.003 \pm 0.003	0.992	0.988 ~ 0.994	0.002
	3	0.011 \pm 0.010	0.996	0.994 ~ 0.997	0.002	0.006
	4	0.039 \pm 0.033	0.998	0.997 ~ 0.998	0.002	0.006
	5	0.072 \pm 0.033	0.998	0.997 ~ 0.998	0.001	0.003
	6	0.104 \pm 0.089	0.960	0.945 ~ 0.972	0.002	0.006
	7	0.210 \pm 0.168	0.908	0.874 ~ 0.935	0.003	0.008
	Z_3^3	2	0.003 \pm 0.003	0.967	0.954 ~ 0.977	0.002
3		0.010 \pm 0.008	0.996	0.987 ~ 0.999	0.001	0.003
4		0.036 \pm 0.031	0.998	0.997 ~ 0.999	0.001	0.003
5		0.052 \pm 0.036	0.952	0.933 ~ 0.966	0.003	0.007
6		0.082 \pm 0.070	0.973	0.970 ~ 0.981	0.003	0.008
7		0.172 \pm 0.152	0.998	0.997 ~ 0.999	0.002	0.008
Z_3^{-1}		2	0.006 \pm 0.006	0.964	0.956 ~ 0.969	0.001

Parameter	Diameter (mm)	Mean \pm SD (μm)	ICC	(95%CI)	S_w (μm)	TRT (μm)
	3	0.021 \pm 0.020	0.995	0.992 ~ 0.996	0.002	0.006
	4	0.052 \pm 0.042	0.999	0.998 ~ 0.999	0.001	0.003
	5	0.081 \pm 0.059	0.939	0.916 ~ 0.957	0.002	0.006
	6	0.135 \pm 0.120	1.000	1.000 ~ 1.000	0.001	0.003
	7	0.258 \pm 0.195	0.969	0.958 ~ 0.973	0.002	0.006
Z_3^{-1}	2	0.003 \pm 0.003	0.988	0.976 ~ 0.990	0.001	0.003
	3	0.012 \pm 0.006	0.989	0.985 ~ 0.992	0.002	0.006
	4	0.038 \pm 0.001	0.986	0.980 ~ 0.990	0.003	0.008
	5	0.070 \pm 0.044	1.000	1.000 ~ 1.000	0.002	0.006
	6	0.119 \pm 0.084	1.000	1.000 ~ 1.000	0.002	0.006
	7	0.205 \pm 0.138	0.937	0.913 ~ 0.956	0.002	0.006

SD: standard deviation; tHOA: total High Order Aberration; Z_4^0 : Spherical Aberration; Z_3^{-3} : vertical trefoil; Z_3^3 : horizontal trefoil; Z_3^{-1} : vertical coma; Z_3^1 : horizontal coma; S_w : within-subject standard deviation; TRT: test-retest repeatability; ICC: intraclass correlation coefficient; r : Pearson correlation coefficient

Correlation analysis of corneal high order aberration and pupil diameter

The values of corneal tHOA, Z_4^0 , Z_3^{-1} , Z_3^1 , Z_3^{-3} and Z_3^3 all increased with increasing pupil diameter, showing a significantly positive correlation between corneal aberration and pupil sizes, with correlation coefficient r of 0.948 ($P=0.004$), 0.902 ($P=0.014$), 0.923 ($P=0.009$), 0.844 ($P=0.034$), 0.901 ($P=0.014$) and 0.934 ($P=0.006$), respectively. In addition, each of corneal high order aberrations Z_3^{-1} , Z_3^1 , Z_3^{-3} , Z_3^3 and Z_4^0 was positively correlated with tHOA. Furthermore, SA (Z_4^0) had the highest correlation with tHOA ($r=0.996$, $P<0.001$), followed by Z_3^3 , Z_3^{-1} , Z_3^{-3} , Z_3^1 with r of 0.993, 0.986, 0.980 and 0.978 ($P\leq 0.001$), respectively. It indicates that among the higher-order aberrations, SA has the greatest effect on visual quality (Fig. 1).

Repeatability of ocular high order aberration

Table 2 summarizes the mean values and repeatability metrics for ocular high order aberration at 3 mm and 5 mm pupil diameter. Measurement of ocular high order aberration also provided the highest

repeatability as *ICC* higher than 0.9, *S_w* and *TRT* lower than 0.01 μm and 0.10 μm , respectively. The ocular tHOA and SA were $0.050 \pm 0.016 \mu\text{m}$ and $0.010 \pm 0.008 \mu\text{m}$ respectively at 3 mm pupil diameter, and $0.240 \pm 0.090 \mu\text{m}$ and $0.073 \pm 0.052 \mu\text{m}$ respectively at 5 mm pupil diameter.

Table 2
Repeatability of ocular high order aberration

Parameter	Diameter (mm)	Mean \pm SD (μm)	ICC	(95%CI)	<i>S_w</i> (μm)	<i>TRT</i> (μm)
tHOA	3	0.050 ± 0.016	0.993	0.990 ~ 0.995	0.001	0.003
	5	0.240 ± 0.090	0.998	0.997 ~ 0.998	0.001	0.003
Z_4^0	3	0.010 ± 0.008	0.972	0.961 ~ 0.981	0.001	0.003
	5	0.073 ± 0.052	0.999	0.999 ~ 0.999	0.007	0.020
Z_3^{-3}	3	0.017 ± 0.013	0.965	0.951 ~ 0.975	0.002	0.006
	5	0.062 ± 0.037	0.919	0.889 ~ 0.943	0.001	0.003
Z_3^3	3	0.054 ± 0.034	0.986	0.981 ~ 0.990	0.002	0.006
	5	0.013 ± 0.011	0.993	0.990 ~ 0.995	0.008	0.022
Z_3^{-1}	3	0.022 ± 0.013	0.968	0.955 ~ 0.977	0.002	0.006
	5	0.101 ± 0.054	0.991	0.987 ~ 0.993	0.005	0.014
Z_3^1	3	0.013 ± 0.010	0.961	0.946 ~ 0.973	0.002	0.006
	5	0.068 ± 0.035	0.977	0.968 ~ 0.984	0.005	0.014

SD: standard deviation; tHOA: total High Order Aberration; Z_4^0 : Spherical Aberration; Z_3^{-3} : vertical trefoil; Z_3^3 : horizontal trefoil; Z_3^{-1} : vertical coma; Z_3^1 : horizontal coma; *S_w*: within-subject standard deviation; *TRT*: test-retest repeatability; *ICC*: intraclass correlation coefficient; *r*: Pearson correlation coefficient

Discussion

It is essential to know about the repeatability of instruments under normal conditions to establish its validity in clinical practices and studies. The i.Profiler^{Plus}, as a wavefront autorefractor, can provide the quantification of both objective refraction and wavefront aberration[10–12]. More information about this device is needed as growing interest in image quality assessment for refractive surgery design, intraocular lens selection, contact lenses evaluation, corneal diseases diagnose, and so forth[13–16]. The present study might provide evidence to help learn more about this wavefront-based device.

The present study showed a high repeatability for measuring corneal and ocular HOAs by i.Profiler, with ICC (both greater than 0.9) and S_w (both less than $0.01\mu\text{m}$). Meanwhile, this study verified that the values of corneal HOA [SA (Z_4^0), coma (Z_3^{-1} , Z_3^1), and trefoil (Z_3^{-3} , Z_3^3)] and tHOA significantly depended on the pupil diameters; at 2mm ~ 7mm pupil diameter, these values all rose with the increase of pupil diameter. At 3mm pupil diameter, the amount of ocular HOAs was found to be comparable to the previous studies[17]. When the pupil diameter was $\geq 5\text{mm}$, the increase amplitude of SA became the largest. It implied that SA plays an important role in the factors influencing visual quality. Randazzo[18] pointed out that when the pupil diameter was $\geq 5\text{mm}$, SA doubled for every 1mm increase, which was consistent with the results of this study. Raymond et al.[19] also compared the corneal HOAs at 3mm ~ 7mm pupil size, and found that HOAs increased with the pupil dilation, among which the corneal SA had the largest variation.

SA, as the variation of focus with aperture, has a great impact on the image quality. With the increase of pupil size, the diffuse spot centered on the optical axis becomes larger and the visual quality becomes worse. In this study, the cornea and ocular SA showed larger ICC and smaller S_w values under different pupil diameters. The TRT values of SA at all pupil diameters were not more than $0.020\mu\text{m}$, except for the TRT of corneal SA (Z_4^0) with $0.022\mu\text{m}$ at 7mm pupil, indicating that the repeatability of measuring corneal and ocular SA with i.Profiler was excellent. The results also showed that the corneal SA was $0.049 \pm 0.016\mu\text{m}$ and $0.270 \pm 0.040\mu\text{m}$ at 4 mm and 6 mm pupil diameters respectively, which were close to our previous measurements of $0.05 \pm 0.03\mu\text{m}$ and $0.28 \pm 0.07\mu\text{m}$ by a wavefront aberration instrument KR-1W based on Hartmann-Shack principle[20]. Similarly, Beiko et al.[21] also obtained a corneal SA value of $0.270 \pm 0.089\mu\text{m}$ at pupil diameter of 6mm by measuring 696 healthy subjects earlier.

Unlike SA, coma and trefoil is not on-axis aberration with axial symmetry. The decentration of pupil increases coma and trefoil, so pupil size is associated with both. In this study, ICC and S_w of the coma and trefoil are similar to these of SA at different pupil. ICC values of negative vertical coma (Z_3^{-1}) even reached 1.0 at 6mm pupil diameter. Likewise, all the TRT values of coma and trefoil were not more than $0.020\mu\text{m}$, except for ocular trefoil (Z_3^3) $0.022\mu\text{m}$ at 5mm pupil diameter. These data all indicated that the repeatability was excellent in measuring the coma and trefoil of cornea and oculi with i.Profiler. It was also found that the corneal and ocular Z_3^{-1} was larger than Z_3^1 , and this trend increased with the increase of pupil diameter. Studies have shown that a vertical coma increased the depth of field on the vertical meridian and helps improve reading[22, 23]. This feature was used in the optical surface of rotationally asymmetric multifocal IOL (intraocular lens) and was correlated with postoperative visual acuity corresponding to near defocus[24]. In addition, Omaret al.[25] compared the HOAs in keratoconus before and after CXL (corneal collagen cross-linking), and suggested that the corneal vertical coma and trefoil could add value beside keratometric readings.

Ocular aberrations consist of corneal and intraocular (mainly lenticular) aberrations. In this study, the corneal SA at 3mm (mesopic) and 5mm (scotopic) pupil diameter were $0.016 \pm 0.007\mu\text{m}$ and $0.116 \pm 0.031\mu\text{m}$ respectively, while the ocular SA were $0.010 \pm 0.008\mu\text{m}$ and $0.073 \pm 0.052\mu\text{m}$ respectively. The

ocular SA was smaller than corneal SA at the same pupil diameters, thus intraocular SA in young adults is negative. Just like the coupling of two optical systems, the corneal positive aberration and lenticular negative aberrations tend to neutralize each other, thereby achieving optimal image quality and visual function. In our previous studies, it was also confirmed that aspheric IOL can compensate corneal SA and reduce ocular SA, and improve the postoperative visual quality in the darkness[20]. Moreover, the i.Profiler^{Plus} is capable of obtaining measurements for pupil sizes of 2 to 7 mm. As shown by the measurements, the aberrations are pupil size dependent. This needs to be taken into special consideration when measuring different participants or under different conditions, especially when the measurements are used for clinical applications such as corneal refractive surgery and refractive cataract surgery.

In the present study, a few deficiencies were found in the i.Profiler^{Plus}. For example, only corneal and ocular aberrations but not intraocular aberrations could be directly measured; further, ocular aberrations were provided only with the pupil diameter of 3mm and 5mm. The values of Kappa angle and Alpha angle were also not available. The improvement in these aspects will facilitate the device to be widely used in clinical practice. This study also had its limitations. Firstly, the included subjects were all normal young volunteers, so the accuracy of the device in measuring diseases affecting the refractive transparency (e.g., cataract) remains to be determined. Secondly, the inclusion criteria did not include moderate to severe refractive errors, so the measurement accuracy of the device in this case is not quite clear. In subsequent studies, the sample should be expanded to these participants of different ages, refractive status, and eye diseases.

In summary, the i.Profiler comprehensively evaluates visual quality by measuring both refraction and wavefront aberrations. The present study demonstrates that measurements of wavefront aberrations by i.Profiler are highly repeatable. The i.Profiler can be used as a reliable aberrometer to measure wavefront aberrations in the clinical practice.

Declarations

Acknowledgment

This work was supported by the Key Project of Sichuan Health and Family Planning Commission (18ZD022) and the Key Project of Nanchong City and University Cooperation (18SXHZ0492).

Compliance with ethical standards

Conflict of Interest: The authors declare that they have no conflict of interest.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the Institutional Review Board of Affiliated Hospital of North Sichuan Medical College and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

References

1. Kim J, Choi SH, Lim DH, Yoon GJ, Chung TY (2020) Comparison of Outcomes After Topography-Modified Refraction Versus Wavefront-Optimized Versus Manifest Topography-Guided LASIK. *BMC Ophthalmol* 20:192. <https://doi.org/10.1186/s12886-020-01459-0>
2. Masiwa LE, Moodley V (2020) A review of corneal imaging methods for the early diagnosis of pre-clinical Keratoconus. *J Optom* 13:269–275. <https://doi.org/10.1016/j.optom.2019.11.001>
3. Hughes RP, Vincent SJ, Read SA, Collins MJ (2020) Higher order aberrations, refractive errodevelopment and myopia control: a review. *Clin Exp Optom* 103:68–85. <https://doi.org/10.1111/cxo.12960>
4. Carracedo G, Carpena-Torres C, Batres L, Serramito M, Gonzalez-Bergaz A (2020) Comparison of Two Wavefront Autorefractors: Binocular Open-Field versus Monocular Closed-Field. *J Ophthalmol* 3:8580471. <https://doi.org/10.1155/2020/8580471>
5. Garzón N, García-Montero M, López-Artero E, Poyales F, Albarrán-Diego C (2019) Influence of trifocal intraocular lenses on standard autorefraction and aberrometer-based autorefraction. *J Cataract Refract Surg* 45:1265–1274. <https://doi.org/10.1016/j.jcrs.2019.04.017>. Epub 2019 Jul 17
6. Lebow KA, Campbell CE (2014) A comparison of a traditional and wavefront autorefraction. *Optom Vis Sci* 91:1191–1198. <https://doi.org/10.1097/OPX.0000000000000378>
7. Rauscher FG, Lange H, Yahiaoui-Doktor M, Tegetmeyer H, Blendowske R et al (2019) Agreement and repeatability of noncycloplegic and cycloplegic wavefront-based autorefraction in children. *Optom Vis Sci* 96:879–889. <https://doi.org/10.1097/OPX.0000000000001444>
8. Mcalinden C, Khadka J, Pesudovs K (2015) Precision (repeatability and reproducibility) studies and sample-size calculation. *J Cataract Refract Surg* 41:2598–2604. <https://doi.org/10.1016/j.jcrs.2015.06.029>
9. Muller R, Buttner P (2010) A critical discussion of intraclass correlation coefficients. *Stat Med* 13:2465–2476. <https://doi.org/10.1002/sim.4780132310>
10. Truckenbrod C, Meigen C, Brandt M, Vogel M, Wahl S, Jurkutat A, Kiess W (2020) Reference curves for refraction in a German cohort of healthy children and adolescents. *PLoS One* 15:0230291. <https://doi.org/10.1371/journal.pone.0230291>. eCollection 2020
11. Putnam NM, Vasudevan B, Juarez A, Le CT, Sam K, de Gracia PD, Hoppert A (2019) Comparing habitual and i. Scription refractions. *BMC Ophthalmol* 19:49. <https://doi.org/10.1186/s12886-019-1053-x>
12. Hartwig A, Atchison DA, Radhakrishnan H (2013) Higher-order aberrations and anisometropia. *Curr Eye Res* 38:215–219. <https://doi.org/10.3109/02713683.2012.738462>. Epub 2012 Nov 15
13. Ye-wei Yin Y, Zhao Xiao-ying, Wu Meng-yang, Jiang Xiao-bo, Xia Y, Chen Wei-tao, Song, Sheng-fa Hu, Xia Zhou, Kelly Young, Dan Wen (2019) One-year effect of wearing orthokeratology lenses on the

- visual quality of juvenile myopia: a retrospective study. *Peer J* 7:6998.
<https://doi.org/10.7717/peerj.6998>
14. Naderan M, Jahanrad A, Farjadnia M (2017) Ocular, corneal, and internal aberrations in eyes with keratoconus, forme fruste keratoconus, and healthy eyes. *Int Ophthalmol* 38:1565–1573.
<https://doi.org/10.1007/s10792017-0620-5>
 15. Koh S (2018) Irregular astigmatism and higher-order aberrations in eyes with dry eye disease. *Invest Ophthalmol Vis Sci* 59:36–40. <https://doi.org/10.1167/iovs.17-23500>
 16. Hoshing A, Samant M, Bhosale S, Naik A, Naik AM (2019) Comparison of higher order aberrations in amblyopic and non-amblyopic eyes in pediatric patients with anisometropic amblyopia. *Indian J Ophthalmol* 67:1025–1029. <https://doi.org/10.4103/ijo.IJO-1625-18>
 17. Levy Y, Segal O, Avni I, Zadok D (2005) Ocular higher-order aberrations in eyes with supernormal vision. *Am J Ophthalmol* 139:225–228. <https://doi.org/10.1016/j.ajo.2004.08.035>
 18. Randazzo A, Nizzola F, Rossetti L, Orzalesi N, Vinciguerra P (2005) Pharmacological management of night vision disturbances after refractive surgery: Results of a randomized clinical trial. *J Cataract Refract Surg* 31:1764–1772. <https://doi.org/10.1016/j.jcrs.2005.02.042>
 19. Applegate RA, Donnelly WJ, Marsack JD, Koenig DE, Pesudovs K (2007) Three-dimensional relationship between high-order root-mean-square wavefront error, pupil diameter, and aging. *J Opt Soc Am A Opt Image Sci Vis* 24:578–587. <https://doi.org/10.1364/josaa.24.000578>
 20. Xuan Liao X-Q, Haung C-J, Lan Q-Q, Tan B-W, Wen J, Lin J, Tian (2019) Comprehensive evaluation of retinal image quality in comparing different aspheric to spherical intraocular lens implants. *Curr Eye Res* 44:1098–1103. <https://doi.org/10.1080/02713683.2019.1615512>
 21. Beiko GH, Haigis W, Steinmueller A (2007) Distribution of corneal spherical aberration in a comprehensive ophthalmology practice and whether keratometry can predict aberration values. *J Cataract Refract Surg* 33:848–858. <https://doi.org/10.1016/j.jcrs.2007.01.035>
 22. Alió JL, Plaza-Puche AB, Piñero DP, Javaloy J, Ayala MJ (2011) Comparative analysis of the clinical outcomes with 2 multifocal intraocular lens models with rotational asymmetry. *J Cataract Refract Surg* 37:1605–1614. <https://doi.org/10.1016/j.jcrs.2011.03.054>
 23. Venter JA, Barclay D, Pelouskova M, Bull CEL (2014) Initial experience with a new refractive rotationally asymmetric multifocal intraocular lens. *J Refract Surg* 30:770–776.
<https://doi.org/10.3928/1081597X-20141021-09>
 24. Ramón ML, Piñero DP, Pérez-Cambrodí RJ (2012) Correlation of visual performance with quality of life and intraocular aberrometric profile in patients implanted with rotationally asymmetric multifocal IOLs. *J Refract Surg* 28:93–99. <https://doi.org/10.3928/1081597X-20111213-02>
 25. Omar IAN, Zein HA (2019) Accelerated epithelium-off corneal collagen cross-linking for keratoconus:12-month results. *Clin Ophthalmol* 13:2385–2394.
<https://doi.org/10.2147/OPHTH.S232118>

Figures

Image not available with this version

Figure 1

Correlation analysis of corneal high order aberration and pupil diameter (PD: pupil diameter; tHOA: total High Order Aberration; SA: fourth order (Z40) Spherical Aberration; Z3-3: vertical trefoil; Z33: horizontal trefoil; Z3-1: vertical coma; Z31: horizontal coma; a: $P < 0.05$; b: $P < 0.01$)