

Repeatability of Wavefront Aberration Measurements With a Placido-Based Topographer in Normal and Keratoconic Eyes

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ABSTRACT

PURPOSE: To determine and compare the repeatability of anterior corneal higher order aberrations (HOAs) using a Placido-based topographer (Allegro Topolyzer; WaveLight Technologie AG, Alcon Laboratories, Erlangen, Germany) in a sample of normal and keratoconic eyes.

METHODS: Three repeated measurements of each cornea of normal and keratoconic eyes were taken with the Allegro Topolyzer. Repeatability of the HOAs (3rd- and 4th-order individual values and normalized polar Zernike coefficients, coma-like, root mean square (RMS) up to 8th-order values, HOA RMS, and total RMS for 6-mm pupil diameter) and central corneal power (3-mm pupil) were analyzed. Within-subject standard deviation (S_w), precision, repeatability, coefficient of variation (CV), and the intraclass correlation coefficient (ICC) were calculated.

RESULTS: Zernike coefficients were significantly different between the normal (36 eyes of 36 patients) and keratoconus (36 eyes of 36 patients) groups ($P \leq .03$) except in Z_{-3}^{+1} , Z_{-3}^{+3} , Z_{-4}^{+4} , and Z_{-4}^{+4} . In the normal group, S_w was 0.031 μm or less, CV ranged from 6.49% (spherical aberration) to 37.18% (secondary astigmatism), and ICC values ranged from 0.227 to 0.982. In the keratoconus group, S_w was 0.059 μm or less, CV ranged from 2.06% (total RMS) to 25.82% (tetrafoil), and ICC values ranged from 0.839 to 0.996. In analyzing the keratoconus stages (Amsler-Krumeich classification), the repeatability of the Zernike coefficients tended to improve with increasing keratoconus stage.

CONCLUSIONS: The repeatability of corneal wavefront aberration provided by the Allegro Topolyzer was better in keratoconic eyes (good and moderate repeatability) than in normal eyes (moderate and poor repeatability). These results are important to eye care practitioners and refractive surgeons during refractive surgery planning or keratoconus detection, classification, and management.

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avefront aberrations can be defined as differences from the perfect optical system, in which the rays that form the image of a point coincide in a single point.¹ In the eye, wavefront aberrations can be divided into two types: low order aberrations, which can be corrected using spectacles (sphere and cylinder), and higher order aberrations (HOAs), which cannot be corrected with standard methods.^{1,2} Wavefront analysis allows a detailed assessment of the corneal surface (corneal wavefront) or the entire eye (wavefront).¹

Currently, HOA assessment is important in corneal refractive surgery in the development of custom ablations based on corneal topography,³ intraocular lens implantation,⁴ contact lens fitting,⁵ myopia control,⁶ or the diagnosis and follow-up of irregular or ectatic corneal conditions (eg, keratoconus, pellucid marginal degeneration, or iatrogenic ectasia).⁷ Moreover, the aberration measurements of the anterior corneal surface have been used in the identification and gradation of the severity of keratoconus disease,^{8,9} particularly in early cases without slit-lamp findings.¹⁰

The Allegro Topolyzer (WaveLight Technologie AG, Alcon Laboratories, Erlangen, Germany) is a computerized Placido-based videokeratography system that was developed for use in refractive surgery procedures. The Allegro Topolyzer cor-

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neal topographer is exportable and can be linked with the WaveLight Excimer Laser systems, allowing customized, topography-guided surgical treatments.³

The success of clinical applications of wavefront analysis depends on the repeatability of the topographic corneal data measurements.² Moreover, knowledge of repeatability is mandatory to introduce any device into clinical practice,¹¹ but, to the best of our knowledge, there are no previous reports on the intrasubject repeatability of the Allegro Topolyzer for wavefront aberrations in normal and keratoconic eyes. Thus, the aim of the current study was to determine and compare the repeatability of the anterior corneal surface HOAs provided by the Allegro Topolyzer in a sample of normal and keratoconic eyes.

PATIENTS AND METHODS

This study was a prospective, clinic-based, observational and single-masked investigation.

PATIENTS

The patients in this study were divided into the following two study groups: normal and keratoconic eyes. A randomly selected single eye of each patient was chosen for the study. Independent corneal specialists confirmed the diagnosis of keratoconus after a complete eye examination, which included Scheimpflug analysis and anterior eye biomicroscopy assessment. The keratoconus stage was identified using the Amsler–Krumeich classification.¹²

Patients with any active ocular surface disease, corneal opacities, glaucoma, use of medication that could affect ocular physiology, or a history of any type of ocular surgery, pellucid marginal corneal degeneration, or corneal astigmatism greater than 2.00 diopters (D) (except in the keratoconus group) were excluded. Eyes with stage 4 keratoconus according to the Amsler–Krumeich classification were also excluded from the study to guarantee an optimal quality of corneal topography. Normal patients showed a corrected distance visual acuity of 20/20 and refractive errors of ± 5.00 diopters. Contact lens wear was discontinued for at least 2 weeks before the eye examination.

Informed consent was obtained from each patient after the Human Sciences Ethics Committee of the University of Valladolid approved the study. All patients were treated in accordance with the tenets of the Declaration of Helsinki.

INSTRUMENTATION

The Allegro Topolyzer is a diagnostic device based on the Placido disk system supported by 22 measurement rings with 22,000 elevation points. Its software

module allows data transfer from the Allegro Topolyzer to the WaveLight Excimer Laser systems and enables customized topography-guided treatments. A Zernike analysis of the anterior corneal surface up to the 8th order was computed.

MEASUREMENT PROCEDURE

Three separate measurements of each cornea were taken with the Allegro Topolyzer topographer (Examination Software Version 1.76r45 FW1.19) following the manufacturer's guidelines in a darkened room. The patients were asked to perform a complete blink just before each measurement to spread an optically smooth tear film over the cornea. The patients moved their chin from the chinrest between scans to eliminate the interdependence of successive measurements. The patients were repositioned and the device was realigned after each measurement. Poor quality topographies with an "Analyze Area" value less than 70% were deleted (these included artefacts from tear film or movement and shadows from eyelids, eyelashes, or nose). The same experienced operator performed all measurements and the device was calibrated before the study.

MEASUREMENTS OBTAINED

The individual values of Zernike coefficients of the 3rd [Z_{-3}^{-3} ; Z_{-3}^{-1} ; Z_{-3}^{+1} ; Z_{-3}^{+3}] and 4th [Z_{-4}^{-4} ; Z_{-4}^{-2} ; Z_{-4}^0 ; Z_{-4}^{+2} ; Z_{-4}^{+4}] orders of each corneal assessment were collected from the Allegro Topolyzer display (Option Display – Zernike Analysis of the Software Version 1.76r45 FW1.19). The normalized polar Zernike coefficients (coma [Z_{-3}^{+1}]; trefoil [Z_{-3}^{+3}], secondary astigmatism [Z_{-4}^{+2}]; and tetrafoil [Z_{-4}^{+4}]) that combine the paired terms in the same order to give a single value (ie, the 3rd-order coma [Z_{-3}^{+1}] was obtained with the combination of vertical coma [Z_{-3}^{-1}] and horizontal coma [Z_{-3}^{+1}]) were also recorded. Root mean square (RMS) (3rd to 8th order), HOA RMS (3rd to 8th order), and total RMS (1st to 8th order) also calculated for each corneal assessment. Coma-like (3rd, 5th, and 7th order) was analyzed for its usefulness in keratoconus classification.⁹ All wavefront measurements were recorded with a 6-mm optic diameter. Maximum and minimum anterior corneal powers in the 3-mm zone were also recorded in all patients. The Allegro Topolyzer provided the individual values of Zernike coefficients in Malacara notation,¹³ but the results are presented in Optical Society of America standard notation to compare with previous studies.^{14,15} Malacara notation was converted to Optical Society of America standard notation following the manufacturer recommendations (the orientation of the Zernike coefficients were swapped, maintaining the coefficient value in microns).

STATISTICAL ANALYSIS

Statistical analysis was performed using SPSS for Windows software (version 15.0; SPSS, Inc., Chicago, IL). The intraobserver repeatability of the set of three consecutive measurements of each wavefront coefficient was calculated using the following five parameters: within-subject standard deviation (S_w),¹⁶ intrasubject precision ($1.96 \times S_w$, which shows the error range for 95% of the repeated measurements and the true value),¹⁶ repeatability ($2.77 \times S_w$, which defines the difference between two measurements of the same patient for 95% of pairs of observation),¹⁶ coefficient of variation (CV; percentage value of the measurement's variation and defined as the ratio of the S_w to the overall mean [$CV = S_w/\text{mean} \times 100 (\%)$]),¹⁶ and the intraclass correlation coefficient (ICC; classified as follows: less than 0.75 = poor agreement; 0.75 to less than 0.90 = moderate agreement; 0.90 or greater = high agreement).¹⁷ The CV of the individual Zernike coefficients was not computed because the mean values for individual Zernike coefficients can be positive or negative.

A normal distribution of variables was assessed using the Kolmogorov–Smirnov test ($P > .05$ indicated that the data were normally distributed). Differences between normal and keratoconic eyes in all HOA data and between all calculated repeatability coefficients (S_w , precision, repeatability, CV, and ICC) were compared with non-parametric Mann–Whitney U tests ($P < .05$ were considered significant). Differences between the aberrometric measurements by the keratoconus stage according to the Amsler–Krumeich classification were also calculated with a non-parametric Kruskal–Wallis analysis of variance ($P < .05$ were considered significant) to assess the diagnostic and classification utility of the HOAs in management of patients with keratoconus. If significant differences between keratoconus stages were detected, a pairwise analysis was conducted (Mann–Whitney U with Bonferroni correction was used, and a P value of $.05/3 = .0017$ was used to judge significance).

RESULTS

Intraobserver repeatability was analyzed in 72 eyes of 72 patients divided into two study groups (normal and keratoconus). In the normal group, 36 eyes of 36 patients (28 women, 8 men) were included, with a mean age of 29.4 ± 8.2 years (range: 19 to 50 years) and a mean spherical equivalent refractive error of -1.47 ± 1.75 D (range: $+1.50$ to -5.00 D). Thirty-six eyes of 36 patients with keratoconus (11 women, 25 men) comprised the keratoconus group (12 keratoconic eyes in stage I, 12 eyes in stage II, and 12 eyes in stage III, ac-

ording to the Amsler–Krumeich classification); the mean age of this group was 36.9 ± 10.5 years (range: 19 to 58 years) and the mean spherical equivalent refractive error was -4.45 ± 4.25 D (range: -0.50 to -14.00 D). Maximum and minimum anterior corneal powers and their repeatability assessment by group are shown in **Table 1**.

Table A (available in the online version of this article) shows the intraobserver repeatability results for the wavefront aberrations in normal and keratoconic eyes. All modal pairs were significantly different between the normal and keratoconus groups ($P \leq .03$) except in Z^{+1}_3 , Z^{+3}_3 , Z^{-4}_4 , and Z^{+4}_4 . In the normal group, the S_w was $0.031 \mu\text{m}$ or less, the CV ranged from 6.49% for spherical aberration to 37.18% for secondary astigmatism, and the ICC values ranged from 0.502 to 0.982 for Zernike coefficients and from 0.227 to 0.925 for RMS values. In the keratoconus group, the S_w was $0.059 \mu\text{m}$ or less, the CV ranged from 2.06% for HOA total RMS to 25.82% for tetrafoil, and the ICC values ranged from 0.943 to 0.996 for Zernike coefficients and from 0.839 to 0.996 for RMS values.

Intraobserver repeatability results of the wavefront aberrations analyzed by keratoconus stage are summarized in **Table B** (available in the online version of this article). The mean value of all normalized polar Zernike coefficients and RMS values tended to increase (in absolute magnitude) from stage I to stage III (**Figure 1**). The S_w was $0.064 \mu\text{m}$ or less in three stages of keratoconus and the CV decreased (better repeatability) with increasing keratoconus stage in coma, trefoil, coma-like, and 3rd- and 4th-order HOAs, and total RMS value (**Figure 2**).

DISCUSSION

In the current study, the repeatability of maximum and minimum corneal powers provided by the Allegro Topolyzer were analyzed, and we found excellent repeatability and agreement measurements in normal and keratoconic eyes (**Table 1**). Only one study of corneal power repeatability using the Allegro Topolyzer has been published and demonstrated similar results to our study in a normal sample of patients ($CV \leq 0.29\%$ and $ICC \geq 0.993$); however, the study did not investigate repeatability in keratoconic eyes.¹⁸

For the total anterior corneal wavefront measurements, we found that the repeatability tended to be better in keratoconic eyes than in normal eyes (**Table A**). In both groups, the repeatability of Zernike coefficients was better at the center of the Zernike pyramid than for coefficients along the periphery of the Zernike pyramid at the 3rd and 4th order.

TABLE 1
**Intraobserver Repeatability for Maximum and Minimum Corneal Power (D)
 in Normal and Keratoconic Eyes**

Parameter	Mean ± SD (D) (Range)	S _w (D)	Precision (D)	Repeatability (D)	CV (%)	ICC (95% CI)
Maximum corneal power (D)						
Keratoconus	47.61 ± 3.16 (42.70 to 55.57)	0.21	0.42	0.59	0.44	0.998 (0.996 to 0.999)
Normal	44.11 ± 1.32 (41.06 to 46.00)	0.13	0.25	0.35	0.29	0.996 (0.992 to 0.998)
P ^a	< .01	.03	.04	.04	.01	–
Stage I	45.55 ± 2.10 (42.70 to 49.10)	0.19	0.38	0.54	0.43	0.994 (0.985 to 0.998)
Stage II	47.74 ± 3.06 (42.90 to 53.80)	0.19	0.37	0.52	0.39	0.998 (0.994 to 0.999)
Stage III	49.54 ± 3.06 (45.70 to 55.57)	0.25	0.49	0.70	0.50	0.997 (0.992 to 0.999)
P ^b	< .01 ^c	.51	.51	.51	.66	–
Minimum corneal power (D)						
Keratoconus	45.05 ± 2.79 (40.33 to 51.93)	0.08	0.16	0.23	0.43	0.997 (0.995 to 0.998)
Normal	43.33 ± 1.35 (40.23 to 45.70)	0.11	0.21	0.30	0.25	0.997 (0.994 to 0.998)
P ^a	< .01	.36	.36	.36	.04	–
Stage I	44.13 ± 1.97 (40.33 to 47.87)	0.06	0.12	0.17	0.43	0.994 (0.985 to 0.998)
Stage II	45.17 ± 3.15 (40.43 to 51.00)	0.09	0.17	0.24	0.41	0.997 (0.993 to 0.999)
Stage III	45.86 ± 3.06 (40.70 to 51.93)	0.10	0.20	0.29	0.44	0.998 (0.994 to 0.999)
P ^b	.28	.16	.16	.16	.87	–

D = diopters; SD = standard deviation; S_w = within-subject standard deviation; CV = coefficient of variation; ICC = intraclass correlation coefficient; CI = confidence interval

^aMann-Whitney U analysis of variance between normal and keratoconic eyes.

^bKruskal-Wallis analysis of variance between stages of keratoconus.

^cMann-Whitney U analysis of variance. Statistically significant difference between stages I and III.

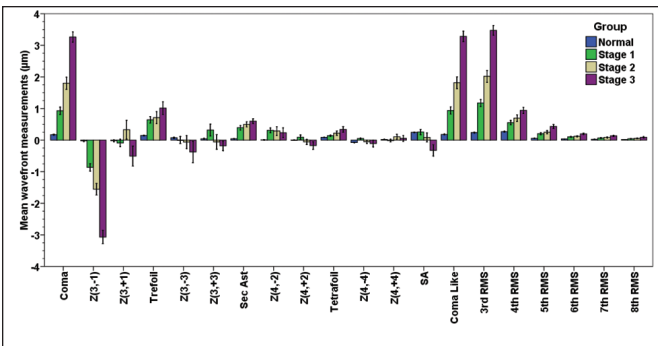


Figure 1. Mean value of corneal wavefront measurements (µm) in keratoconus stages. RMS = root mean square; sec ast = secondary astigmatism; SA = spherical aberration

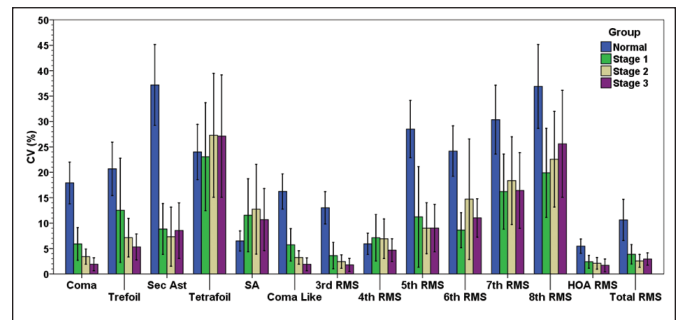


Figure 2. Mean value of coefficient of variation (%) of Zernike coefficients in keratoconus stages. CV = coefficient of variation; sec ast = secondary astigmatism; SA = spherical aberration; RMS = root mean square; HOA = higher order aberration

Comparing the results of wavefront aberration repeatability with previous studies¹⁹⁻²⁴ is complicated because there is no consensus on how to analyze

the data, as shown in **Tables C-D** (available in the online version of this article). Some studies show aberrations as individual values [ie, Z⁻¹₃ and Z⁺¹₃],

whereas others show the normalized polar Zernike coefficients [ie, Z_{3}^{+1}] and analyze the anterior cornea surface, the posterior cornea surface, or the entire cornea (both surfaces), depending on the device used. Furthermore, not all published studies calculated the CV of the normalized polar Zernike coefficients, which causes a loss of important information. The advantage of the CV is that it is a unitless number and is consequently independent of the units of observation in which the measurement has been taken. In contrast, the S_w of data (calculated in all studies included in **Tables C-D**) must always be understood in the context of the mean of the Zernike data in the sample analyzed (ie, keratoconic eyes have a higher mean value than normal eyes). Therefore, it is difficult to compare the results of various published studies using different samples and devices, and the same problem occurs with the precision and repeatability values. This comparison of several studies of wavefront aberration repeatability emphasizes the need to establish a consensus to facilitate comparison between the results of various studies and devices; for example, CV of the normalized polar Zernike coefficients should be included to permit a repeatability comparison of various devices. Moreover, all devices should show the Zernike coefficients in the Optical Society of America standard notation to make a comparison between results. A limitation of the Allegro Topolyzer is that it presents the individual Zernike coefficients in Malacara notation and hinders comparison with other studies.

In the normal group (**Table B**), the spherical aberration presented high repeatability (CV = 6.43% and ICC = 0.948) except in Z_{3}^{-1} and Z_{3}^{+1} (ICCs \geq 0.917). The trefoil, secondary astigmatism, and tetrafoil (including individual Zernike values) showed poor repeatability. These trends are in agreement with other studies,^{19,20,22} in which the spherical aberration and coma shows higher levels of wavefront repeatability than the rest of the Zernike coefficients in normal eyes (**Table C**). Our results were slightly better than other previously reported findings¹¹ of the Sirius device, which analyzes anterior HOAs in spherical aberration (ICC = 0.824) and coma (ICC = 0.856). In summary, the Allegro Topolyzer presents repeatability values for Zernike coefficients similar to those previously reported in normal eyes with better agreement in coma and spherical aberration than trefoil, secondary astigmatism, and tetrafoil (individual values and normalized polar Zernike coefficients).

In regard to aberration wavefront repeatability in patients with keratoconus, there are few reports on this topic,^{11,23,24} and only one study has analyzed the ante-

rior corneal surface wavefront, in which keratoconus classifications were based on the HOAs of the anterior corneal surface⁹ (**Table D**). We found a high agreement (ICCs \geq 0.905) among all Zernike coefficients (individual values and normalized polar Zernike coefficients) except in 7th- and 8th-order HOAs and total RMS that showed moderate agreement (ICCs \geq 0.839) (**Table B**). Bayhan et al.¹¹ reported the repeatability of the Sirius topographer in keratoconic eyes (n = 41) and analyzed normalized polar Zernike coefficients and found high agreement in coma, trefoil, secondary astigmatism, and spherical aberration (ICCs \geq 0.930), with the worst results in tetrafoil (ICC = 0.809). This finding is consistent with our results, in which the tetrafoil presented the highest CV (25.82%).

One of the main contributions of the current study is the analysis of repeatability at various keratoconus stages that, to the best of our knowledge, has not been previously reported. Generally, the Zernike coefficient repeatability tended to be better with increasing keratoconus stage (**Table C**). This finding may be because the HOAs are greater and clearly defined with increasing keratoconus stage, so their measurement could be more repeatable and useful to disease classification.

The Zernike coefficients reveal differences between stages I, II, and III of keratoconus (according to the Amsler–Krumeich classification) in the mean value of coma, vertical coma (Z_{3}^{-1}), coma-like, 3rd-order RMS, HOA RMS, and total RMS (**Table C**). Further research is necessary to determine if these findings can be used in diagnosing, managing, and classifying keratoconus.⁹ Currently, this study demonstrated that coma, coma-like, vertical coma (Z_{3}^{-1}), and 3rd-order RMS could be the most useful aberration coefficients for keratoconus detection^{25,26} and classification⁹ because these coefficients show statistical differences between the three keratoconus stages (**Table C**). Alió and Shabayek⁹ proposed a modification in the Amsler–Krumeich classification to consider the coma-like (3rd, 5th, and 7th order) values based on the aberrometry analysis of 40 keratoconic eyes (coma-like criteria: stage I > 1.50 to 2.50 μm ; stage II > 2.50 to \leq 3.50 μm ; stage III > 3.50 to \leq 4.50 μm , and stage IV > 4.50 μm). However, we found a lower coma-like value in all studied stages than in the proposed coma-like values in these classification criteria. Our results suggest that this classification should be used with caution in clinical practice because coma-like values could depend on the device. More studies with larger samples of patients with keratoconus would be needed to support a classification rule using corneal wavefront aberrations.

Finally, external factors influenced the measurement of the aberrations and may have significantly reduced the repeatability of corneal HOA measurements; these factors include saccadic eye movements,²⁷ misalignment of patients' head in the forehead and chin rest that produces variations in pupil center location,²⁸ and changes in tear film stability after blinking that could not be detected by the operator during topography acquisition. However, a carefully controlled data acquisition could control the quality of the image capture and minimize the effect of these external factors on HOA measurements.²⁹ Consequently, the difficulty in obtaining highly repeatable HOA measurements might arise from small eye movements and their continuous adaptation in attaining the best optical image rather than the inability of the device to provide repeatable measurements.

CONCLUSIONS

For the first time, a HOA repeatability assessment with the Allegro Topolyzer was conducted and described in keratoconic and normal eyes. The results of this study are important to eye care practitioners and refractive surgeons for management of patients who have undergone refractive surgery or have keratoconus.

Generally, the HOA repeatability was moderate and poor for Zernike coefficients in normal eyes; it was better at the center of the Zernike pyramid than along the periphery of the Zernike pyramid in the 3rd and 4th order.

Keratoconic eyes presented good HOA repeatability, except in tetrafoil and RMS up to the 7th-order, which had moderate repeatability. Coma, vertical coma (Z^{-1}_3), coma-like, 3rd-order RMS, HOA RMS, and total RMS would help in keratoconus detection, management, and future disease stage classification.

AUTHOR CONTRIBUTIONS

Study concept and design (SO-T, GR, VJ, RM); data collection (SO-T, GR, VJ, RM); analysis and interpretation of data (SO-T, GR, VJ); writing the manuscript (SO-T, GR, VJ, RM); critical revision of the manuscript (SO-T, GR, RM); statistical expertise (SO-T, GR, VJ, RM); administrative, technical, or material support (RM); supervision (RM)

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TABLE A
**Intraobserver Repeatability for Total Corneal Wavefront Measurements
of Allegro Topolyzer (6-mm Optic Diameter)**

Parameter	Mean ± SD (μm) (Range)	S _w (μm)	Precision (μm)	Repeatability (μm)	CV (%)	ICC (95% CI)
Coma						
Keratoconus	1.999 ± 1.075 (0.417 to 4.209)	0.055	0.108	0.152	3.74	0.995 (0.992 to 0.998)
Normal	0.174 ± 0.084 (0.036 to 0.350)	0.026	0.050	0.071	17.91	0.884 (0.809 to 0.934)
P ^a	< .01	< .01	< .01	< .01	< .01	–
Z ⁻¹ ₃						
Keratoconus	-1.827 ± 1.058 (-4.150 to -0.352)	0.059	0.115	0.162	–	0.994 (0.990 to 0.997)
Normal	-0.020 ± 0.121 (-0.250 to 0.184)	0.031	0.060	0.085	–	0.917 (0.861 to 0.953)
P ^a	< .01	< .01	< .01	< .01	–	–
Z ⁺¹ ₃						
Keratoconus	-0.088 ± 0.833 (-1.982 to 1.703)	0.041	0.088	0.113	–	0.996 (0.993 to 0.998)
Normal	-0.019 ± 0.147 (-0.258 to 0.341)	0.017	0.048	0.046	–	0.982 (0.969 to 0.990)
P ^a	.95	< .01	< .01	< .01	–	–
Trefoil						
Keratoconus	0.790 ± 0.521 (0.151 to 2.339)	0.042	0.082	0.116	8.33	0.989 (0.981 to 0.994)
Normal	0.148 ± 0.048 (0.038 to 0.232)	0.027	0.054	0.076	20.68	0.633 (0.460 to 0.775)
P ^a	< .01	.17	.17	.17	< .01	–
Z ⁻³ ₃						
Keratoconus	-0.142 ± 0.718 (-2.065 to 2.029)	0.050	0.098	0.138	–	0.993 (0.988 to 0.996)
Normal	0.075 ± 0.095 (-0.191 to 0.203)	0.029	0.056	0.080	–	0.876 (0.798 to 0.930)
P ^a	< .01	< .01	< .01	< .01	–	–
Z ⁺³ ₃						
Keratoconus	0.027 ± 0.604 (-1.588 to 1.044)	0.045	0.088	0.124	–	0.990 (0.983 to 0.995)
Normal	0.043 ± 0.086 (-0.127 to 0.187)	0.024	0.048	0.067	–	0.881 (0.805 to 0.933)
P ^a	.717	.04	.04	.04	–	–
Secondary astigmatism						
Keratoconus	0.498 ± 0.235 (0.081 to 0.899)	0.032	0.063	0.089	8.23	0.965 (0.940 to 0.981)
Normal	0.043 ± 0.018 (0.016 to 0.092)	0.014	0.027	0.038	37.18	0.504 (0.308 to 0.682)
P ^a	< .01	< .01	< .01	< .01	< .01	–
Z ⁻² ₄						
Keratoconus	0.278 ± 0.370 (-0.720 to 0.870)	0.037	0.072	0.102	–	0.984 (0.972 to 0.991)
Normal	0.011 ± 0.033 (-0.050 to 0.077)	0.015	0.029	0.041	–	0.771 (0.643 to 0.866)
P ^a	< .01	< .01	< .01	< .01	–	–
Z ⁺² ₄						
Keratoconus	-0.044 ± 0.297 (-0.665 to 0.679)	0.022	0.044	0.062	–	0.991 (0.985 to 0.995)
Normal	0.003 ± 0.030 (-0.066 to 0.056)	0.011	0.022	0.031	–	0.846 (0.751 to 0.912)
P ^a	.03	< .01	< .01	< .01	–	–
Tetrafoil						
Keratoconus	0.233 ± 0.213 (0.042 to 0.869)	0.041	0.081	0.114	25.82	0.946 (0.909 to 0.970)
Normal	0.088 ± 0.030 (0.031 to 0.176)	0.020	0.039	0.055	24.00	0.577 (0.392 to 0.736)
P ^a	< .01	< .01	< .01	< .01	.69	–
Z ⁻⁴ ₄						
Keratoconus	-0.035 ± 0.218 (-0.862 to 0.465)	0.043	0.085	0.120	–	0.943 (0.903 to 0.968)
Normal	-0.074 ± 0.037 (-0.164 to -0.015)	0.022	0.044	0.062	–	0.634 (0.462 to 0.776)
P ^a	.31	< .01	< .01	< .01	–	–
Z ⁺⁴ ₄						
Keratoconus	0.049 ± 0.217 (-0.265 to 0.800)	0.037	0.073	0.103	–	0.954 (0.923 to 0.975)
Normal	0.021 ± 0.032 (-0.050 to 0.068)	0.019	0.037	0.052	–	0.640 (0.469 to 0.780)
P ^a	.31	< .01	< .01	< .01	–	–
Z ⁰ ₄ spherical aberration						
Keratoconus	0.006 ± 0.479 (-1.102 to 0.746)	0.032	0.063	0.089	11.66	0.993 (0.988 to 0.996)
Normal	0.247 ± 0.065 (0.094 to 0.376)	0.014	0.027	0.038	6.49	0.948 (0.912 to 0.971)
P ^a	< .01	< .01	< .01	< .01	.13	–
Coma like (3rd, 5th, and 7th order)						
Keratoconus	2.013 ± 1.078 (0.410 to 4.225)	0.054	0.106	0.150	3.62	0.996 (0.992 to 0.998)
Normal	0.180 ± 0.082 (0.056 to 0.351)	0.025	0.049	0.070	16.23	0.879 (0.801 to 0.931)
P ^a	< .01	< .01	< .01	< .01	< .01	–

TABLE A (cont'd)

Intraobserver Repeatability for Total Corneal Wavefront Measurements of Allegro Topolyzer (6-mm Optic Diameter)

Parameter	Mean \pm SD (μm) (Range)	S_w (μm)	Precision (μm)	Repeatability (μm)	CV (%)	ICC (95% CI)
3rd-order RMS						
Keratoconus	2.222 \pm 1.052 (0.752 to 4.327)	0.049	0.096	0.136	2.61	0.996 (0.993 to 0.998)
Normal	0.239 \pm 0.070 (0.120 to 0.394)	0.030	0.058	0.082	13.02	0.761 (0.629 to 0.860)
P^a	< .01	.10	.10	.10	< .01	–
4th-order RMS						
Keratoconus	0.731 \pm 0.314 (0.216 to 1.651)	0.040	0.078	0.110	6.24	0.974 (0.956 to 0.986)
Normal	0.269 \pm 0.061 (0.151 to 0.393)	0.014	0.027	0.038	5.93	0.925 (0.874 to 0.958)
P^a	< .01	< .01	< .01	< .01	.81	–
5th-order RMS						
Keratoconus	0.296 \pm 0.179 (0.077 to 0.897)	0.025	0.048	0.068	9.76	0.953 (0.920 to 0.974)
Normal	0.057 \pm 0.017 (0.025 to 0.092)	0.016	0.032	0.045	28.51	0.281 (0.078 to 0.499)
P^a	< .01	.34	.34	.34	< .01	–
6th-order RMS						
Keratoconus	0.141 \pm 0.066 (0.045 to 0.327)	0.016	0.031	0.044	11.46	0.905 (0.843 to 0.947)
Normal	0.037 \pm 0.009 (0.022 to 0.059)	0.013	0.026	0.037	24.17	0.382 (0.177 to 0.587)
P^a	< .01	.08	.08	.08	< .01	–
7th-order RMS						
Keratoconus	0.097 \pm 0.053 (0.021 to 0.289)	0.015	0.029	0.041	17.00	0.896 (0.828 to 0.941)
Normal	0.026 \pm 0.009 (0.016 to 0.051)	0.009	0.017	0.024	30.36	0.227 (0.026 to 0.450)
P^a	< .01	< .01	< .01	< .01	< .01	–
8th-order RMS						
Keratoconus	0.063 \pm 0.042 (0.016 to 0.253)	0.014	0.027	0.038	22.69	0.839 (0.741 to 0.908)
Normal	0.019 \pm 0.007 (0.009 to 0.043)	0.008	0.015	0.022	36.90	0.235 (0.029 to 0.458)
P^a	< .01	.02	.02	.02	< .01	–
HOA RMS (3rd to 8th order)						
Keratoconus	2.391 \pm 1.052 (0.833 to 4.427)	0.045	0.088	0.125	2.06	0.997 (0.994 to 0.998)
Normal	0.376 \pm 0.053 (0.284 to 0.495)	0.020	0.040	0.057	5.46	0.788 (0.666 to 0.877)
P^a	< .01	< .01	< .01	< .01	< .01	–
Total RMS (1st to 8th order)						
Keratoconus	7.425 \pm 3.888 (2.352 to 16.525)	0.217	0.425	0.601	3.62	0.995 (0.991 to 0.997)
Normal	1.093 \pm 0.388 (0.467 to 2.039)	0.102	0.201	0.283	16.23	0.865 (0.779 to 0.923)
P^a	< .01	< .01	< .01	< .01	< .01	–

SD = standard deviation; S_w = within-subject standard deviation; *CV* = coefficient of variation; *ICC* = intraclass correlation coefficient; *CI* = confidence interval; *RMS* = root mean square; *HOA* = higher order aberration

^aMann-Whitney U analysis of variance.

The Allegro Topolyzer is manufactured by Alcon Laboratories, Erlangen, Germany.

TABLE B
**Intraobserver Repeatability for Total Corneal Wavefront Measurements
(6-mm Optic Diameter) in Different Stages of Keratoconus**

Parameter	Mean ± SD (μm) (Range)	S _w (μm)	Precision (μm)	Repeatability (μm)	CV (%)	ICC (95% CI)
Coma						
Stage I	0.929 ± 0.382 (0.417 to 1.455)	0.054	0.106	0.150	5.99	0.995 (0.986 to 0.998)
Stage II	1.802 ± 0.564 (0.779 to 2.874)	0.055	0.107	0.152	3.41	0.997 (0.992 to 0.999)
Stage III	3.265 ± 0.487 (2.610 to 4.209)	0.056	0.108	0.154	1.91	0.993 (0.983 to 0.998)
P ^a	< .01 ^{b,c,d}	.56	.56	.56	.01 ^c	–
Z ⁻¹ ₃						
Stage I	-0.861 ± 0.393 (-1.388 to -0.352)	0.062	0.121	0.170	–	0.993 (0.980 to 0.998)
Stage II	-1.522 ± 0.543 (-2.846 to -0.573)	0.050	0.098	0.139	–	0.997 (0.991 to 0.999)
Stage III	-3.068 ± 0.619 (-4.156 to -1.973)	0.064	0.126	0.178	–	0.988 (0.968 to 0.996)
P ^a	< .01 ^{b,c,d}	.51	.51	.51	–	–
Z ⁺¹ ₃						
Stage I	-0.088 ± 0.339 (-0.603 to 0.442)	0.039	0.077	0.108	–	0.996 (0.989 to 0.999)
Stage II	0.330 ± 0.879 (-1.746 to 1.703)	0.034	0.066	0.094	–	0.997 (0.993 to 0.999)
Stage III	-0.505 ± 0.932 (-1.982 to 0.865)	0.049	0.096	0.136	–	0.996 (0.989 to 0.999)
P ^a	< .01 ^{b,d}	.23	.23	.23	–	–
Trefoil						
Stage I	0.643 ± 0.288 (0.151 to 1.159)	0.045	0.089	0.129	12.52	0.989 (0.971 to 0.997)
Stage II	0.712 ± 0.288 (0.181 to 2.339)	0.034	0.066	0.094	7.14	0.986 (0.965 to 0.996)
Stage III	1.015 ± 0.048 (0.280 to 2.182)	0.046	0.090	0.127	5.32	0.992 (0.979 to 0.997)
P ^a	< .01 ^{c,d}	.63	.63	.63	.85	–
Z ⁻³ ₃						
Stage I	0.003 ± 0.323 (-0.557 to 0.502)	0.041	0.082	0.156	–	0.996 (0.988 to 0.999)
Stage II	-0.061 ± 0.605 (-0.575 to 1.716)	0.046	0.090	0.127	–	0.990 (0.974 to 0.997)
Stage III	-0.374 ± 1.008 (-2.065 to 2.029)	0.062	0.122	0.172	–	0.992 (0.979 to 0.998)
P ^a	< .01 ^c	.56	.56	.56	–	–
Z ⁺³ ₃						
Stage I	0.319 ± 0.533 (-0.602 to 1.044)	0.042	0.083	0.017	–	0.991 (0.977 to 0.997)
Stage II	-0.056 ± 0.683 (-1.588 to 0.716)	0.042	0.082	0.117	–	0.984 (0.958 to 0.995)
Stage III	-0.180 ± 0.446 (-0.790 to 0.526)	0.050	0.098	0.138	–	0.994 (0.983 to 0.998)
P ^a	< .01 ^c	.34	.34	.34	–	–
Secondary astigmatism						
Stage I	0.394 ± 0.203 (0.097 to 0.787)	0.029	0.058	0.082	8.83	0.938 (0.845 to 0.980)
Stage II	0.498 ± 0.245 (0.081 to 0.871)	0.022	0.043	0.061	7.32	0.987 (0.967 to 0.996)
Stage III	0.601 ± 0.214 (0.194 to 0.899)	0.044	0.087	0.123	8.53	0.954 (0.884 to 0.985)
P ^a	< .01 ^c	.37	.37	.37	.72	–
Z ⁻² ₄						
Stage I	0.309 ± 0.222 (0.050 to 0.756)	0.033	0.064	0.091	–	0.952 (0.879 to 0.985)
Stage II	0.289 ± 0.411 (-0.586 to 0.870)	0.029	0.057	0.081	–	0.994 (0.986 to 0.998)
Stage III	0.236 ± 0.444 (-0.720 to 0.856)	0.049	0.096	0.135	–	0.976 (0.937 to 0.992)
P ^a	.80	.21	.21	.21	–	–
Z ⁺² ₄						
Stage I	0.093 ± 0.212 (-0.219 to 0.407)	0.019	0.037	0.052	–	0.995 (0.985 to 0.995)
Stage II	-0.055 ± 0.239 (-0.570 to 0.399)	0.017	0.033	0.047	–	0.993 (0.981 to 0.998)
Stage III	-0.170 ± 0.363 (-0.665 to 0.679)	0.031	0.061	0.087	–	0.987 (0.966 to 0.996)
P ^a	< .01 ^c	.08	.08	.08	–	–
Tetrafoil						
Stage I	0.140 ± 0.058 (0.051 to 0.217)	0.027	0.052	0.074	23.09	0.879 (0.717 to 0.960)
Stage II	0.220 ± 0.206 (0.042 to 0.806)	0.042	0.083	0.117	27.28	0.970 (0.924 to 0.991)
Stage III	0.338 ± 0.270 (0.064 to 0.869)	0.055	0.108	0.153	27.12	0.941 (0.853 to 0.981)
P ^a	.01 ^c	.33	.33	.33	.80	–
Z ⁻⁴ ₄						
Stage I	0.049 ± 0.062 (-0.091 to 0.164)	0.029	0.057	0.081	–	0.939 (0.848 to 0.980)
Stage II	-0.050 ± 0.153 (-0.323 to 0.168)	0.044	0.087	0.123	–	0.973 (0.930 to 0.991)
Stage III	-0.106 ± 0.324 (-0.862 to 0.465)	0.057	0.111	0.157	–	0.892 (0.744 to 0.964)
P ^a	< .01 ^{b,c}	.20	.20	.20	–	–
Z ⁺⁴ ₄						
Stage I	-0.016 ± 0.125 (-0.210 to 0.192)	0.032	0.063	0.089	–	0.947 (0.868 to 0.983)
Stage II	0.108 ± 0.229 (-0.115 to 0.738)	0.037	0.072	0.102	–	0.962 (0.904 to 0.988)
Stage III	0.056 ± 0.026 (-0.027 to 0.800)	0.057	0.083	0.117	–	0.948 (0.870 to 0.983)
P ^a	.06	.27	.27	.27	–	–

TABLE B (cont'd)
**Intraobserver Repeatability for Total Corneal Wavefront Measurements
(6-mm Optic Diameter) in Different Stages of Keratoconus**

Parameter	Mean ± SD (µm) (Range)	S _w (µm)	Precision (µm)	Repeatability (µm)	CV (%)	ICC (95% CI)
Z ₄ ⁰ spherical aberration						
Stage I	0.258 ± 0.252 (-0.206 to 0.585)	0.029	0.057	0.081	11.55	0.978 (0.942 to 0.993)
Stage II	0.084 ± 0.423 (-0.421 to 0.716)	0.032	0.062	0.088	12.74	0.998 (0.995 to 0.999)
Stage III	-0.323 ± 0.524 (-1.102 to 0.746)	0.035	0.069	0.098	10.69	0.994 (0.985 to 0.998)
P ^a	< .01 ^{c,d}	.51	.51	.51	.98	–
Coma like (3rd, 5th and 7th order)						
Stage I	0.938 ± 0.397 (0.410 to 1.471)	0.053	0.104	0.147	5.73	0.952 (0.880 to 0.985)
Stage II	1.819 ± 0.567 (0.795 to 2.874)	0.054	0.105	0.149	3.28	0.988 (0.968 to 0.996)
Stage III	3.287 ± 0.505 (2.614 to 4.225)	0.056	0.110	0.156	1.90	0.981 (0.950 to 0.994)
P ^a	< .01 ^{b,c,d}	.56	.56	.56	.02 ^c	–
3rd-order RMS						
Stage I	1.175 ± 0.344 (0.752 to 1.644)	0.044	0.086	0.121	3.61	0.997 (0.991 to 0.999)
Stage II	2.019 ± 0.555 (1.338 to 2.930)	0.047	0.091	0.129	2.43	0.996 (0.989 to 0.999)
Stage III	3.473 ± 0.446 (2.805 to 4.327)	0.057	0.111	0.157	1.78	0.994 (0.984 to 0.998)
P ^a	< .01 ^{b,c,d}	.27	.27	.27	.30	–
4th-order RMS						
Stage I	0.555 ± 0.204 (0.216 to 0.839)	0.036	0.071	0.100	7.13	0.943 (0.958 to 0.982)
Stage II	0.695 ± 0.314 (0.342 to 1.386)	0.163	0.072	0.101	6.92	0.990 (0.973 to 0.997)
Stage III	0.941 ± 0.286 (0.709 to 1.651)	0.046	0.091	0.128	4.68	0.962 (0.903 to 0.988)
P ^a	< .01 ^{c,d}	.55	.55	.55	.86	–
5th-order RMS						
Stage I	0.204 ± 0.092 (0.081 to 0.348)	0.027	0.053	0.074	11.24	0.972 (0.927 to 0.991)
Stage II	0.252 ± 0.147 (0.077 to 0.539)	0.017	0.033	0.047	9.01	0.950 (0.875 to 0.984)
Stage III	0.433 ± 0.193 (0.145 to 0.897)	0.030	0.059	0.083	9.02	0.950 (0.874 to 0.984)
P ^a	< .01 ^{c,d}	.06	.06	.06	.99	–
6th-order RMS						
Stage I	0.103 ± 0.031 (0.045 to 0.149)	0.001	0.017	0.026	8.63	0.951 (0.876 to 0.984)
Stage II	0.123 ± 0.052 (0.048 to 0.243)	0.016	0.031	0.043	14.72	0.892 (0.745 to 0.965)
Stage III	0.199 ± 0.067 (0.110 to 0.327)	0.022	0.043	0.061	11.03	0.773 (0.519 to 0.921)
P ^a	< .01 ^{c,d}	.05	.05	.05	.68	–
7th-order RMS						
Stage I	0.067 ± 0.031 (0.021 to 0.137)	0.011	0.021	0.029	16.21	0.861 (0.680 to 0.954)
Stage II	0.089 ± 0.049 (0.034 to 0.188)	0.015	0.029	0.040	18.37	0.946 (0.866 to 0.983)
Stage III	0.135 ± 0.052 (0.081 to 0.289)	0.019	0.038	0.053	16.41	0.816 (0.594 to 0.937)
P ^a	< .01 ^{c,d}	.08	.08	.08	.96	–
8th-order RMS						
Stage I	0.044 ± 0.024 (0.016 to 0.082)	0.008	0.016	0.023	19.90	0.943 (0.857 to 0.982)
Stage II	0.054 ± 0.031 (0.021 to 0.121)	0.013	0.025	0.035	22.58	0.702 (0.406 to 0.892)
Stage III	0.092 ± 0.052 (0.049 to 0.253)	0.020	0.039	0.055	25.60	0.403 (0.045 to 0.743)
P ^a	< .01 ^{c,d}	.03 ^c	.03 ^c	.03 ^c	.67	–
HOA RMS						
Stage I	1.347 ± 0.359 (0.833 to 1.812)	0.034	0.067	0.094	2.40	0.998 (0.994 to 0.999)
Stage II	2.178 ± 0.568 (1.430 to 3.276)	0.043	0.084	0.119	2.09	0.996 (0.989 to 0.999)
Stage III	3.649 ± 0.411 (3.057 to 4.427)	0.058	0.114	0.165	1.70	0.995 (0.987 to 0.998)
P ^a	< .01 ^{b,c,d}	.33	.33	.33	.60	–
Total RMS						
Stage I	3.788 ± 1.295 (2.352 to 5.827)	0.154	0.301	0.426	3.86	0.991 (0.977 to 0.997)
Stage II	6.427 ± 1.324 (3.516 to 8.841)	0.163	0.320	0.453	2.56	0.998 (0.995 to 0.999)
Stage III	12.060 ± 2.459 (8.247 to 16.525)	0.334	0.654	0.925	2.39	0.993 (0.981 to 0.998)
P ^a	< .01 ^{b,c,d}	.02 ^c	.02 ^c	.02 ^c	.45	–

SD = standard deviation; S_w = within-subject standard deviation; CV = coefficient of variation; ICC = intraclass correlation coefficient; CI = confidence interval; RMS = root mean square; HOA = higher order aberration

^aStatistically significant differences between the three study groups (Kruskal–Wallis analysis of variance).

^bStatistically significant differences between keratoconus stages I and II (Mann–Whitney U analysis of variance).

^cStatistically significant differences between keratoconus stages I and III (Mann–Whitney U analysis of variance).

^dStatistically significant differences between keratoconus stages II and III (Mann–Whitney U analysis of variance).

The Allegro Topolyzer is manufactured by Alcon Laboratories, Erlangen, Germany.

TABLE C
Summary of Previous Reports of Corneal Wavefront Repeatability in Healthy Eyes

Parameter	Current Study	Wang et al. ²⁰	Cerviño et al. ¹⁹	Aramberri et al. ²²	Aramberri et al. ²²	Bayhan et al. ¹¹	López-Miguel et al. ²¹
Device	Allegro Topolyzer	Galilei G3	Galilei G4	Pentacam HR	Galilei G2	Sirius	Topcon KR-1W
Corneal surface	Anterior	Total	Total	Total	Total	Anterior	Total
No. of eyes	36	20	25	35	35	30	75
Coma							
Mean	0.174 ± 0.084	0.33 ± 0.15	–	–	–	0.24 ± 0.08	0.181
S _w	0.026	0.08	–	–	–	0.04	0.041
CV	17.91%	29%	–	–	–	–	–
ICC	0.884	0.897	–	–	–	0.856	0.869
Z⁻¹₃							
Mean	-0.020 ± 0.121	-0.06 ± 0.24	-0.068 ± 0.231	-0.04 ± 0.15	-0.04 ± 0.22	–	–
S _w	0.031	0.08	0.076	0.009	0.09	–	–
CV	–	–	–	–	–	–	–
ICC	0.917	0.966	0.849	0.740	0.809	–	–
Z⁺¹₃							
Mean	-0.019 ± 0.147	0.04 ± 0.26	0.013 ± 0.361	0.00 ± 0.11	0.00 ± 0.34	–	–
S _w	0.017	0.10	0.093	0.02	0.13	–	–
CV	–	–	–	–	–	–	–
ICC	0.982	0.945	0.915	0.961	0.868	–	–
Trefoil							
Mean	0.148 ± 0.048	0.23 ± 0.10	–	–	–	0.16 ± 0.07	–
S _w	0.027	0.09	–	–	–	0.04	–
CV	20.68%	37%	–	–	–	–	–
ICC	0.633	0.714	–	–	–	0.750	–
Z⁻³₃							
Mean	0.075 ± 0.095	-0.11 ± 0.15	-0.051 ± 0.164	0.01 ± 0.06	-0.13 ± 0.15	–	–
S _w	0.029	0.12	0.070	0.08	0.13	–	–
CV	–	–	–	–	–	–	–
ICC	0.876	0.775	0.811	0.478	0.477	–	–
Z⁺³₃							
Mean	0.043 ± 0.086	-0.07 ± 0.11	-0.011 ± 0.128	0.00 ± 0.05	0.00 ± 0.15	–	–
S _w	0.024	0.011	0.076	0.05	0.15	–	–
CV	–	–	–	–	–	–	–
ICC	0.881	0.667	0.552	0.509	0.510	–	–
Secondary astigmatism							
Mean	0.043 ± 0.018	0.09 ± 0.05	–	–	–	0.04 ± 0.02	–
S _w	0.014	0.04	–	–	–	0.05	–
CV	37.18%	40%	–	–	–	–	–
ICC	0.504	0.695	–	–	–	0.678	–
Z⁻²₄							
Mean	0.011 ± 0.033	-0.02 ± 0.05	–	–	–	–	–
S _w	0.015	0.05	–	–	–	–	–
CV	–	–	–	–	–	–	–
ICC	0.771	0.682	–	–	–	–	–
Z⁺²₄							
Mean	0.003 ± 0.030	-0.02 ± 0.08	–	–	–	–	–
S _w	0.011	0.05	–	–	–	–	–
CV	–	–	–	–	–	–	–
ICC	0.846	0.864	–	–	–	–	–
Tetrafoil							
Mean	0.088 ± 0.030	0.15 ± 0.09	–	–	–	0.06 ± 0.03	–
S _w	0.020	0.09	–	–	–	0.05	–
CV	24%	53%	–	–	–	–	–
ICC	0.577	0.669	–	–	–	0.568	–
Z⁻⁴₄							
Mean	-0.074 ± 0.037	0.01 ± 0.06	–	–	–	–	–
S _w	0.022	0.09	–	–	–	–	–
CV	–	–	–	–	–	–	–
ICC	0.634	0.162	–	–	–	–	–

TABLE C (cont'd)

Summary of Previous Reports of Corneal Wavefront Repeatability in Healthy Eyes

Parameter	Current Study	Wang et al. ²⁰	Cerviño et al. ¹⁹	Aramberri et al. ²²	Aramberri et al. ²²	Bayhan et al. ¹¹	López-Miguel et al. ²¹
Z^+4							
Mean	0.021 ± 0.032	-0.07 ± 0.13	-	-	-	-	-
S_w	0.019	0.10	-	-	-	-	-
CV	-	-	-	-	-	-	-
ICC	0.640	0.819	-	-	-	-	-
Spherical aberration							
Mean	0.247 ± 0.065	0.27 ± 0.08	0.121 ± 0.077	0.21 ± 0.06	0.22 ± 0.08	-0.22 ± 0.04	0.085
S_w	0.014	0.02	0.022	0.03	0.04	0.01	0.033
CV	6.49%	7%	-	13.55%	16.26%	-	-
ICC	0.948	0.981	0.857	0.814	0.833	0.824	0.939
Coma-like							
Mean	0.179 ± 0.081	-	-	-	-	-	-0.283 ^a
S_w	0.025	-	-	-	-	-	0.029
CV	16.23%	-	-	-	-	-	-
ICC	0.879	-	-	-	-	-	0.883
3rd-order RMS							
Mean	0.239 ± 0.070	0.42 ± 0.16	-	-	-	-	0.246
S_w	0.030	0.09	-	-	-	-	0.038
CV	13.02%	23%	-	-	-	-	-
ICC	0.761	0.878	-	-	-	-	0.883
4th-order RMS							
Mean	0.269 ± 0.061	0.34 ± 0.09	-	-	-	-	0.168
S_w	0.014	0.06	-	-	-	-	0.029
CV	5.93%	14%	-	-	-	-	-
ICC	0.925	0.825	-	-	-	-	0.876
5th-order RMS							
Mean	0.057 ± 0.017	0.09 ± 0.04	-	-	-	-	-
S_w	0.016	0.03	-	-	-	-	-
CV	28.51%	24%	-	-	-	-	-
ICC	0.281	0.806	-	-	-	-	-
6th-order RMS							
Mean	0.037 ± 0.009	0.06 ± 0.02	-	-	-	-	-
S_w	0.013%	0.02	-	-	-	-	-
CV	24.17%	29%	-	-	-	-	-
ICC	0.382	0.787	-	-	-	-	-
7th-order RMS							
Mean	0.026 ± 0.009	-	-	-	-	-	-
S_w	0.009	-	-	-	-	-	-
CV	30.36%	-	-	-	-	-	-
ICC	0.227	-	-	-	-	-	-
8th-order RMS							
Mean	0.019 ± 0.007	-	-	-	-	-	-
S_w	0.008	-	-	-	-	-	-
CV	36.90%	-	-	-	-	-	-
ICC	0.235	-	-	-	-	-	-
HOAs RMS							
Mean	0.376 ± 0.053	0.56 ± 0.14 ^b	-	0.11 ± 0.03	0.59 ± 0.20	0.41 ± 0.06 ^c	-
S_w	0.020	0.09	-	0.03	0.12	0.07	-
CV	5.46%	14%	-	23.96%	20.26%	-	-
ICC	0.788	0.858	-	0.564	0.687	0.824	-
Total RMS							
Mean	1.093 ± 0.388	-	-	-	-	0.91 ± 0.37 ^c	-
S_w	0.102	-	-	-	-	0.07	-
CV	16.23%	-	-	-	-	-	-
ICC	0.865	-	-	-	-	0.976	-

S_w = within-subject standard deviation; CV = coefficient of variation; ICC = intraclass correlation coefficient; RMS = root mean square; HOA = higher order aberration

^aComa-like 3rd and 5th Zernike order.

^bUp to the 7th Zernike order.

^c3rd to 6th Zernike order.

TABLE D
**Summary of Previous Reports of
 Corneal Wavefront Repeatability in Keratoconic Eyes**

Parameter	Current Study	Bayhan et al. ¹¹	Sideroudi et al. ²³	Jinabhai et al. ²⁴
Device	Allegro Topolyzer	Sirius	Pentacam	IRX-3 aberrometer
Cornea surface	Anterior	Anterior	Posterior	Ocular
No. of eyes	36	41	33	31
Coma				
Mean	1.999 ± 1.075	2.22 ± 1.33	7.6 ± 4.6	0.85
S _w	0.055	0.03	0.258	0.06
CV	3.74%	–	–	–
ICC	0.995	0.988	0.997	–
Z⁻¹₃				
Mean	-1.827 ± 1.058	–	-6.653 ± 3.939	–
S _w	0.059	–	0.209	–
CV	–	–	–	–
ICC	0.994	–	0.997	–
Z⁺¹₃				
Mean	-0.088 ± 0.833	–	-0.154 ± 3.697	–
S _w	0.041	–	0.236	–
CV	–	–	–	–
ICC	0.996	–	0.993	–
Trefoil				
Mean	0.790 ± 0.521	0.70 ± 0.36	–	0.54
S _w	0.042	0.05	–	0.07
CV	8.33%	–	–	–
ICC	0.989	0.930	–	–
Z⁻³₃				
Mean	-0.142 ± 0.718	–	0.064 ± 1.208	–
S _w	0.050	–	0.216	–
CV	–	–	–	–
ICC	0.993	–	0.672	–
Z⁺³₃				
Mean	0.027 ± 0.604	–	-0.178 ± 0.427	–
S _w	0.045	–	0.127	–
CV	–	–	–	–
ICC	0.990	–	0.846	–
Secondary astigmatism				
Mean	0.498 ± 0.235	0.45 ± 0.28	–	0.40
S _w	0.032	0.04	–	0.07
CV	8.23%	–	–	–
ICC	0.965	0.976	–	–
Z⁻²₄				
Mean	0.278 ± 0.370	–	0.007 ± 0.220	–
S _w	0.037	–	0.263	–
CV	–	–	–	–
ICC	0.984	–	0.952	–
Z⁺²₄				
Mean	-0.044 ± 0.297	–	-0.187 ± 0.183	–
S _w	0.022	–	0.232	–
CV	–	–	–	–
ICC	0.991	–	0.878	–
Tetrafoil				
Mean	0.233 ± 0.213	0.18 ± 0.09	–	0.33
S _w	0.041	0.04	–	0.08
CV	25.82%	–	–	–
ICC	0.946	0.809	–	–
Z⁻⁴₄				
Mean	-0.035 ± 0.218	–	-0.002 ± 0.411	–
S _w	0.043	–	0.207	–
CV	–	–	–	–
ICC	0.943	–	0.806	–

TABLE D (cont'd)
**Summary of Previous Reports of
 Corneal Wavefront Repeatability in Keratoconic Eyes**

Parameter	Current Study	Bayhan et al. ¹¹	Sideroudi et al. ²³	Jinabhai et al. ²⁴
Z^{+4}_4				
Mean	0.049 ± 0.217	–	0.273 ± 0.238	–
S_w	0.037	–	0.260	–
CV	–	–	–	–
ICC	0.954	–	0.988	–
Spherical aberration				
Mean	0.006 ± 0.479	0.15 ± 0.38	-0.376 ± 1.125	0.34
S_w	0.032	0.03	0.127	0.09
CV	11.63%	–	–	–
ICC	0.993	0.956	0.956	–
Coma-like				
Mean	2.013 ± 1.078	–	7.677 ± 4.615 ^a	–
S_w	0.054	–	0.262	–
CV	3.62%	–	–	–
ICC	0.996	–	0.997	–
3rd-order RMS				
Mean	2.222 ± 1.052	–	–	–
S_w	0.049	–	–	–
CV	2.61%	–	–	–
ICC	0.996	–	–	–
4th-order RMS				
Mean	0.731 ± 0.314	–	–	–
S_w	0.040	–	–	–
CV	6.24%	–	–	–
ICC	0.974	–	–	–
5th-order RMS				
Mean	0.296 ± 0.179	–	–	–
S_w	0.025	–	–	–
CV	9.76%	–	–	–
ICC	0.953	–	–	–
6th-order RMS				
Mean	0.141 ± 0.066	–	–	–
S_w	0.016	–	–	–
CV	11.46%	–	–	–
ICC	0.905	–	–	–
7th-order RMS				
Mean	0.097 ± 0.053	–	–	–
S_w	0.015	–	–	–
CV	17.00%	–	–	–
ICC	0.896	–	–	–
8th-order RMS				
Mean	0.063 ± 0.042	–	–	–
S_w	0.014	–	–	–
CV	22.69%	–	–	–
ICC	0.839	–	–	–
HOAs RMS				
Mean	2.391 ± 1.052	2.49 ± 1.32 ^b	7.94 ± 0.43 ^b	0.93 ^a
S_w	0.045	0.03	0.275	0.07
CV	22.69%	–	–	–
ICC	0.839	0.979	0.996	–
Total RMS				
Mean	7.425 ± 3.888	4.41 ± 1.77 ^c	–	–
S_w	0.217	0.09	–	–
CV	3.62%	–	–	–
ICC	0.865	0.986	–	–

S_w = within-subject standard deviation; CV = coefficient of variation; ICC = intraclass correlation coefficient; RMS = root mean square; HOA = higher order aberration

^a3rd to 5th Zernike order.

^b3rd to 6th Zernike order.

^cUp to the 6th Zernike order.

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