Repeatability of aberrometric measurements in normal and keratoconus eyes using a new Scheimpflug–Placido topographer

Hasan Ali Bayhan, MD, Seray Aslan Bayhan, MD, Ersin Muhafız, MD, İzzet Can, MD

PURPOSE: To evaluate the repeatability of the anterior and posterior corneal wavefront aberrations using the Sirius Scheimpflug–Placido topographer in normal eyes and keratoconus eyes.

SETTING: Bozok University Faculty of Medicine, Yozgat, Turkey.

DESIGN: Evaluation of diagnostic test.

METHODS: In eyes of healthy subjects and eyes of keratoconus patients, 3 repeated measurements were obtained using the Scheimpflug–Placido topographer. Repeatability of the corneal aberrometric data using a 7th-order Zernike expansion (6.0 mm pupil) and central corneal power (3.0 mm zone) in the anterior and posterior corneal surfaces were analyzed. The within-subject standard deviation (S_w) and the intraclass correlation coefficient (ICC) were calculated.

RESULTS: For all modal pairs, the S_w was 0.08 μm or less for anterior and posterior corneal aberrations in both groups. The ICC of the anterior corneal surface ranged from 0.607 (pentafoil) to 0.988 (primary coma) in keratoconus eyes ($n = 41$) and from 0.568 (quadrifoil) to 0.856 (primary coma) in normal eyes ($n = 30$). The ICCs for posterior corneal surface aberrometry were 0.656 to 0.873 and 0.592 to 0.824, respectively. For anterior and posterior corneal curvatures, the S_w was 0.12 or lower and the ICC values were more than 0.93 in all cases except the posterior corneal surface reading at the 3.0 mm corneal area in keratoconus eyes (ICC 0.875).

CONCLUSIONS: The intraexaminer repeatability of most anterior corneal aberrations with the Scheimpflug–Placido system was moderate to high in normal eyes and keratoconus eyes. The system showed moderate repeatability for the posterior corneal surface.

Financial Disclosure: No author has a financial or proprietary interest in any material or method mentioned.

J Cataract Refract Surg 2014; 40:269–275 © 2013 ASCRS and ESCRS

Corneal aberrations are focusing errors caused by imperfections in the corneal shape that prevent light rays from a distant point source from converging into a single image point on the retina. Topographic corneal data are used to compute the wavefront-aberration function, expressing how light is modified as it passes through the cornea.[1] Today, the concepts of wavefront-guided corneal refractive surgery,[2,3] aberration-correcting contact lenses,[4] and wavefront-based custom intraocular lenses[5] have increased interest in studies of higher-order aberrations (HOAs). Custom ablations based on corneal topography data appear to be promising and more predictable.[2,3] Furthermore, corneal-generated wavefront aberrations are good indicators for early detection and grading of keratoconus.[6,7]

At present, the most frequently used topographers are based on Placido-disk, scanning-slit, and Scheimpflug technologies. In contrast to Placido disk–based videokeratoscopes, scanning slit–based and Scheimpflug-based topography technologies enable analysis not only of anterior surface elevations but also of posterior corneal surface elevations.[1] The Sirius Scheimpflug–Placido topographer (Costruzione Strumenti Oftalmici) is a new device using the combination of a rotating Scheimpflug camera and Placido-disk technology. In a single scan, it provides anterior segment imaging and measurements, anterior and posterior corneal topography, wavefront analysis, and corneal pachymetry.

Knowledge of repeatability is essential for a new device to be introduced into clinical practice.

http://dx.doi.org/10.1016/j.jcrs.2013.07.046

Repeatability is defined as the intrasession variability obtained when using the same instrument and operator and repeating the measurement during a short period.[8] Previous studies of the Sirius device showed good intrasession repeatability of anterior segment measurements[9–11] and agreement with other devices.[11] Although these studies have shown the repeatability of this instrument, to our knowledge, none examined the instrument's capability to provide repeatable measurements of anterior and posterior corneal surface aberrations. The aim of this study was to evaluate the repeatability of this new Scheimpflug–Placido topographer in measuring anterior and posterior corneal aberrations in normal eyes and keratoconus eyes.

SUBJECTS AND METHODS

This prospective study comprised eyes of healthy subjects and eyes of keratoconus patients. The local ethics committee approved this study, which followed the tenets of the Declaration of Helsinki. All subjects provided written informed consent.

All eyes in the normal group had a corrected distance visual acuity of 20/20 or better. Subjects with ocular or systemic disease (atopic dermatitis, asthma, or connective tissue disorders), a history of ocular surgery, a familial history of keratoconus, or refractive errors greater than ±1.50 diopters (D) (spherical and/or cylindrical) were excluded from the normal group.

The ocular findings that defined keratoconus were (1) an irregular cornea determined by distorted keratometry mires, distortion of the retinoscopic or ophthalmoscopic red reflex, or a combination and (2) at least 1 of the following biomicroscopic signs: Vogt striae, Fleischer ring, or corneal scarring consistent with keratoconus.[12,13] Keratoconus cases with a history of corneal surgery or with extensive corneal scarring were excluded. Keratoconus was graded according to the criteria of the Collaborative Longitudinal Evaluation of Keratoconus Study Group.[14]

Subjects wearing contact lenses to correct refractive errors were instructed to discontinue the use of soft contact lenses for at least 2 weeks before examination and those wearing rigid gas-permeable contact lenses, for at least 4 weeks before examination. One eye of each subject was chosen for the study according to a random-number sequence (dichotomatic sequence 0 and 1).

The Sirius Scheimpflug–Placido topographer was used to measure corneal topography and the central radii of curvature (calculated in a central 3.0 mm zone). Anterior and posterior corneal wavefront aberrations were computed up to the 7th Zernike order for a 6.0 mm pupil diameter. Because vertical trefoil Z(3,−3), vertical coma Z(3,−1), horizontal coma Z(3,+1), primary spherical aberration Z(4,0), and 2nd-order vertical coma Z(5,−1) coefficients have been shown to be the most relevant for keratoconus detection,[15,16] the Scheimpflug–Placido system automatically combines them and gives the Baiocchi Calossi Versaci front index (BCV_f) and Baiocchi Calossi Versaci back index (BCV_b) values. The BCV_f, expressed in micrometers, was obtained by combining these coefficients (from the anterior corneal surface) and weighting them by a function of the coma axis. Likewise, a linear combination of Z(3,−3), Z(3,−1), Z(3,+1), Z(4,0), and Z(5,−1) and information about the coma axis on the posterior Zernike decomposition defines the BCV_b.[13] In this study, intrasession repeatability of the normalized polar Zernike coefficients that combine the paired terms in the same order (2nd to 5th order), higher-order root mean square (RMS), and total RMS were calculated. Repeatability of the BCV_f and BCV_b indices and anterior and posterior corneal powers (in central 3.0 mm zone) were also recorded.

Measurement Protocol

Measurements with the Scheimpflug–Placido topographer were performed while the device was brought into focus and the subject's eye was aligned along the visual axis by a central fixation light. The subjects were asked to sit back after each measurement, and the device was realigned before the subsequent measurement. The subjects were instructed to blink completely just before each measurement, and 3 measurements were taken. In case of a poor-quality scan with movement artifacts and irregularities (eg, due to misalignment or blinks during the scan), 1 more measurement was taken and the subject was excluded if the new scan was also of poor quality.

Measurement System

The Sirius is a new topography device that combines a monochromatic rotating Scheimpflug camera and a Placido disk. The scanning process acquires a series of 25 Scheimpflug images (meridians) and 1 Placido top-view image to analyze the anterior segment by obtaining 25 radial sections of the cornea and anterior chamber. Anterior surface data from Placido and Scheimpflug images are merged using a proprietary method. All other measurements for internal structures are derived solely from Scheimpflug data. A 475 nm ultraviolet-free blue light–emitting diode light is used to measure 35 632 points for the anterior corneal surface and 30 000 points for the posterior cornea. Corneal aberrometry is obtained using the ray-tracing technique.

Statistical Analysis

Intraobserver repeatability was assessed using the following 4 parameters: within-subject standard deviation (S_w) of 3 consecutive measurements, intrasubject precision, repeatability, and the intraclass correlation coefficient (ICC). The S_w is a simple way of estimating the size of the measurement error. Intrasubject precision was defined as $\pm 1.96 \times S_w$. Precision indicates the size of the range of error of the repeated measurements for 95% of

Submitted: April 10, 2013.
Final revision submitted: July 16, 2013.
Accepted: July 20, 2013.

From Bozok University Medicine Faculty, Ophthalmology Department, Yozgat, Turkey.

Corresponding author: Hasan Ali Bayhan, MD, Bozok University Medicine Faculty, Ophthalmology Department, Yozgat, Turkey. E-mail: alihasanbayhan@hotmail.com.

Table 1. Intrasubject repeatability for the anterior and posterior corneal power (central 3.0 mm) by group.

Parameter	Mean		S_w		Precision		ICC	
	Normal	Keratoconus	Normal	Keratoconus	Normal	Keratoconus	Normal	Keratoconus
K1 ant(D)	42.93 ± 1.28	46.60 ± 2.78	0.06	0.12	0.11	0.23	0.968	0.935
K2 ant(D)	43.76 ± 1.35	51.50 ± 3.77	0.05	0.11	0.09	0.21	0.942	0.985
K1 post (D)	−5.92 ± 0.23	−6.82 ± 0.61	0.04	0.05	0.07	0.09	0.989	0.875
K2 post(D)	−6.28 ± 0.23	−7.84 ± 0.64	0.04	0.04	0.07	0.07	0.973	0.937

ant = anterior; ICC = intraclass correlation coefficient; K1 = keratometry in flat meridian; K2 = keratometry in steep meridian; post = posterior; S_w = within-subject standard deviation

observations. Repeatability, also known as test–retest variability, was calculated by multiplying the S_w by 2.77. The ICC is an analysis of a variance-based type of correlation that measures the relative homogeneity within groups (between the repeated measurements) in ratio to the total variation.[17,18] To make a comparison with previous studies, the coefficient of repeatability (COR) was also calculated; the COR is 1.96 times the standard deviation (SD) of differences between 2 measurements. To calculate the COR, the first and second measurements were selected. A *P* value less than 0.05 was considered statistically significant. All data were analyzed using the SPSS software (version 16.0, SPSS, Inc.) and Medcalc software (version 11.6.0.0, Medcalc Software bvba, Inc.).

RESULTS

This prospective study comprised 30 eyes of 30 healthy subjects and 41 eyes of 41 keratoconus patients. In the keratoconus group, 2 eyes (4.87%) had mild keratoconus, 24 eyes (58.53%) had moderate keratoconus, and 15 eyes (36.6%) had severe keratoconus. The mean age of subjects was 30.06 years ± 6.12 (SD) in the normal group and 29.58 ± 10.45 years in the keratoconus group.

Table 1 shows the anterior and posterior corneal powers (central 3.0 mm) and the results of their repeatability assessment by group. The S_w was 0.12 or lower in all cases. All ICC values associated with the keratometric measurements in both groups were more than 0.93 except the keratometric reading of the posterior corneal surface at the 3.0 mm corneal area in keratoconus eyes.

Table 2 shows the mean wavefront aberrations and SDs in the 2 groups. Table 3 and Table 4 show the repeatability data of anterior corneal aberrations and posterior corneal aberrations, respectively, according to group. For all modal pairs, the S_w was 0.08 μm or less for the anterior and posterior corneal surfaces in both groups. For the anterior corneal surface, the ICC values were 0.607 to 0.988 in keratoconus eyes and 0.568 to 0.856 in normal eyes. The repeatability of the BCV_f and BCV_b indices was excellent in both groups, with ICCs of more than 0.96.

DISCUSSION

High accuracy and repeatability in corneal aberration measurements have become increasingly important in ophthalmic practice. For instance, analysis of corneal aberrations is helpful to the clinician in predicting visual performance,[19] detecting keratoconus,[7] and grading keratoconus.[6] Similarly, in the postoperative evaluation of laser refractive surgery, the decentration and surface irregularity from laser ablation complications can be well described by aberration terms, such as coma and spherical aberration.[20] Most studies of corneal aberrations consider only the anterior corneal surface and neglect the posterior surface.[6,7,21] To provide an accurate description of corneal aberrations, the posterior surface must also be measured. In the current study, we evaluated the repeatability of the aberrations of anterior and posterior corneal surfaces as well as the corneal curvature at the 3.0 mm zone using the Sirius Scheimpflug–Placido topographer.

First, we evaluated the intrasubject repeatability of the anterior and posterior corneal curvature measurements in the 3.0 mm zone. The repeatability of curvature measurements in normal eyes was high, with all ICCs being more than 0.94 and intrasession test–retest repeatability being smaller than 0.16 D. Savini et al.[9] also found an ICC of more than 0.99 (showing excellent repeatability) for most automatic measurements with the same Scheimpflug–Placido topographic system we used. The measurements included mean simulated keratometry, mean pupil corneal power, minimum and apex corneal thicknesses, and aqueous depth. The results of Savini et al. and our results seem to be better than the previously reported anterior and posterior corneal power repeatability measurements of the Orbscan II scanning-slit corneal topographer (Bausch & Lomb) (ICC range 0.70 to 0.93 in normal eyes) and comparable to those using the Pentacam rotating Scheimpflug system (Oculus).[22]

In the present study, the posterior flattest curvature in keratoconus eyes had the lowest ICC value (0.875). This ICC represents a moderate level of repeatability.[23]

Table 2. Mean wavefront aberrations in normal and keratoconus groups.

	Mean Wavefront Aberration (μm) ± SD			
	Normal Group		Keratoconus Group	
Parameter	Anterior	Posterior	Anterior	Posterior
Z(2,±2) astigmatism	0.74 ± 0.37	0.19 ± 0.05	3.48 ± 1.58	0.55 ± 0.41
Z(3,±3) trefoil	0.16 ± 0.07	0.10 ± 0.06	0.70 ± 0.36	0.60 ± 0.32
Z(3,±1) coma	0.24 ± 0.08	0.05 ± 0.02	2.22 ± 1.33	0.44 ± 0.22
Z(4,±4) quadrifoil	0.06 ± 0.03	0.04 ± 0.02	0.18 ± 0.09	0.18 ± 0.09
Z(4,±2) astigmatism II	0.04 ± 0.02	0.02 ± 0.01	0.45 ± 0.28	0.13 ± 0.10
Z(4,0) SA	−0.22 ± 0.04	0.00 ± 0.01	0.15 ± 0.38	−0.10 ± 0.16
Z(5,±5) pentafoil	0.03 ± 0.01	0.03 ± 0.02	0.11 ± 0.08	0.09 ± 0.08
Z(5,±3) trefoil II	0.03 ± 0.02	0.04 ± 0.03	0.10 ± 0.05	0.23 ± 0.12
Z(5,±1) coma II	0.03 ± 0.02	0.01 ± 0.01	0.23 ± 0.19	0.09 ± 0.05
Z(6,±6) esafoil	0.03 ± 0.01	0.02 ± 0.02	0.07 ± 0.05	0.06 ± 0.05
Z(6,±4) quadrifoil II	0.02 ± 0.01	0.02 ± 0.02	0.07 ± 0.04	0.07 ± 0.04
Z(6,±2) astigmatism III	0.02 ± 0.01	0.01 ± 0.01	0.08 ± 0.06	0.08 ± 0.08
Z(6,0) SA II	0.01 ± 0.01	0.00 ± 0.00	−0.01 ± 0.08	0.02 ± 0.06
Z(7,±7) eptafoil	0.02 ± 001	0.02 ± 0.02	0.05 ± 0.03	0.05 ± 0.03
Z(7,±5) pentafoil II	0.02 ± 0.01	0.02 ± 0.02	0.04 ± 0.02	0.04 ± 0.02
Z(7,±3) trefoil III	0.01 ± 0.01	0.02 ± 0.01	0.04 ± 0.02	0.10 ± 0.05
Z(7,±1) coma III	0.01 ± 0.01	0.01 ± 0.01	0.04 ± 0.02	0.04 ± 0.04
Higher-order RMS	0.41 ± 0.06	0.16 ± 0.08	2.49 ± 1.32	0.88 ± 0.41
Total RMS	0.91 ± 0.37	0.26 ± 0.07	4.41 ± 1.77	1.06 ± 0.55
BCV_f	0.18 ± 0.23		3.24 ± 1.81	
BCV_b	0.08 ± 0.13		3.24 ± 1.60	

BCV_b = Baiocchi Calossi Versaci back index; BCV_f = Baiocchi Calossi Versaci front index; RMS = root mean square; SA = spherical aberration

Savini et al.[9] reported a similar ICC of 0.868 for the mean posterior corneal power in keratoconus eyes with the Sirius device.

Montalbán et al.[10] analyzed the repeatability of anterior and posterior curvatures and power vector components at 3.0 mm, 5.0 mm, and 7.0 mm in 61 eyes of 61 keratoconus patients using the same Scheimpflug–Placido system we used. They found an ICC of more than 0.990 in all cases except the posterior flattest curvature at the 3.0 mm zone (ICC,

Table 3. Intrasubject repeatability outcomes for anterior corneal aberrations by group.

	S_w		Precision		Repeatability		COR		ICC	
Parameter	Normal	Keratoconus	Normal	Keratoconus	Normal	Keratoconus	Normal	Keratoconus	Normal	Keratoconus
Z(2,±2) astigmatism	0.08	0.04	0.15	0.08	0.224	0.121	0.66	0.50	0.731	0.982
Z(3,±3) trefoil	0.04	0.05	0.08	0.10	0.113	0.144	0.09	0.27	0.750	0.930
Z(3,±1) coma	0.04	0.03	0.08	0.06	0.113	0.088	0.09	0.29	0.856	0.988
Z(4,±4) quadrifoil	0.05	0.04	0.10	0.08	0.146	0.121	0.05	0.11	0.568	0.809
Z(4,±2) astigmatism II	0.05	0.04	0.09	0.08	0.138	0.116	0.05	0.11	0.678	0.976
Z(4,0) SA	0.01	0.01	0.02	0.02	0.033	0.036	0.05	0.25	0.824	0.956
Z(5,±5) pentafoil	0.02	0.02	0.04	0.05	0.058	0.072	0.03	0.08	0.623	0.607
Z(5,±3) trefoil II	0.01	0.01	0.02	0.02	0.030	0.036	0.03	0.09	0.698	0.641
Z(5,±1) coma II	0.01	0.03	0.02	0.06	0.036	0.088	0.02	0.13	0.823	0.939
Higher-order RMS	0.07	0.03	0.14	0.06	0.196	0.091	0.09	0.49	0.824	0.979
Total RMS	0.07	0.09	0.14	0.17	0.199	0.252	0.11	0.37	0.976	0.986
BCV_f	0.04	0.03	0.08	0.06	0.113	0.094	0.18	0.33	0.976	0.993

BCV_f = Baiocchi Calossi Versaci front index; COR = coefficient of repeatability; ICC = intraclass correlation coefficient; RMS = root mean square; SA = spherical aberration; S_w = within-subject standard deviation

Table 4. Intrasubject repeatability outcomes for the posterior corneal aberrations by group.

	S_w		Precision		Repeatability		COR		ICC	
Parameter	Normal	Keratoconus	Normal	Keratoconus	Normal	Keratoconus	Normal	Keratoconus	Normal	Keratoconus
Z(2,±2) astigmatism	0.01	0.03	0.02	0.06	0.033	0.085	0.09	0.39	0.716	0.873
Z(3,±3) trefoil	0.01	0.04	0.03	0.08	0.038	0.116	0.07	0.33	0.802	0.853
Z(3,±1) coma	0.01	0.03	0.02	0.06	0.030	0.085	0.03	0.25	0.824	0.849
Z(4,±4) quadrifoil	0.01	0.01	0.03	0.03	0.038	0.041	0.07	0.19	0.592	0.739
Z(4,±2) astigmatism II	0.01	0.01	0.02	0.02	0.030	0.036	0.02	0.15	0.691	0.656
Z(4,0) SA	0.01	0.02	0.02	0.04	0.033	0.060	0.03	0.21	0.822	0.833
Z(5,±5) pentafoil	0.01	0.01	0.03	0.03	0.039	0.040	0.05	0.19	0.602	0.779
Z(5,±3) trefoil II	0.01	0.02	0.02	0.04	0.036	0.060	0.05	0.16	0.806	0.797
Z(5,±1) coma II	0.01	0.01	0.02	0.02	0.033	0.036	0.01	0.15	0.756	0.721
Higher order RMS	0.02	0.06	0.04	0.12	0.058	0.166	0.09	0.39	0.840	0.858
Total RMS	0.02	0.08	0.04	0.16	0.060	0.224	0.10	0.35	0.916	0.926
BCV_b	0.02	0.07	0.04	0.13	0.058	0.193	0.16	0.93	0.962	0.971

BCV_b = Baiocchi Calossi Versaci back index; COR = coefficient of repeatability; ICC = intraclass correlation coefficient; RMS = root mean square; SA = spherical aberration; S_w = within-subject standard deviation

0.840) and posterior power vector J0. They reported that the J0 posterior power vector measurements were less repeatable in the central cornea than in larger areas of corneal analysis. The authors speculate that the reason for this might be the inclusion of more points of analysis in large areas, leading to a more complete analysis of the posterior corneal astigmatism, which is commonly highly irregular in the keratoconus cornea.

The corneal front surface contributes approximately one half of the total aberrations of the eye, and the contributions increase substantially with surgery and disease.[24] The higher-order RMS value provides an estimate of the overall magnitude of corneal HOAs. In the present study, the mean posterior corneal HOAs in keratoconus eyes was 0.88 ± 0.41 μm, which was twice as large as the mean anterior corneal HOAs (0.41 ± 0.06 μm) in normal eyes. This finding is consistent with the findings of Chen and Yoon.[25]

Shankar et al.[26] analyzed the intrasession repeatability of the Pentacam system for anterior corneal aberrations over a 6.0 mm pupil by taking 2 readings; the corneal elevation data were fitted with Zernike polynomials up to the 10th order. For comparison with other studies, we arbitrarily selected the first and second measurements to calculate the COR. The COR (0.326) and the mean higher-order RMS value (0.875 μm) in normal eyes reported by Shankar et al. were greater than those in our subjects (COR 0.09; mean 0.41 μm). Wang et al.[27] also reported a better COR (0.235) and a lower mean higher-order RMS (0.56 μm, 3rd to 6th order) with a dual-Scheimpflug Placido topographer (Galilei, Ziemer) for total corneal aberrations in normal eyes than the results reported by Shankar et al.[26] with the Pentacam system. The COR as a percentage of wavefront aberrations for higher-order RMS in keratoconus eyes reported by Shankar et al.[26] with the Pentacam system was also higher than our results (39% versus 19.6%).

Several thousand topographic data points are necessary for adequate detection of corneal surface irregularities that can decrease vision; however, the number of data points measured with wavefront-sensing instruments varies from the low hundreds to the several thousands.[28] With the Pentacam system, 25 images with 500 measurement points on the front and back of the corneal surface are produced.[26] The number of data points evaluated by that system is more than 25 000 (derived solely from 25 Scheimpflug images), while it is much higher with combined Scheimpflug–Placido systems (Sirius ≈100 000 and Galilei >122 000).[1] One possible explanation for the increased magnitude of corneal first-surface wavefront aberrations with the Pentacam system is that the function used to extrapolate from the limited number of corneal slices and datapoints, especially peripherally where the space between samples is the widest, induces noise that is misfitted as aberration.

In the current study, the repeatability for spherical aberration of the anterior and posterior corneal surfaces was moderate to high, with ICCs ranging between 0.822 and 0.956 in normal eyes and keratoconus eyes. In a previous study using the single-Scheimpflug photography system (Pentacam), Piñero et al.[29] found an ICC of more than 0.9 for spherical aberration of the posterior corneal surface in normal eyes. The authors also emphasized that the primary and secondary spherical aberrations were the only coefficients to have acceptable precision values. Wang et al.[27] using the Galilei system found a higher ICC value (0.981) than our results for total corneal spherical aberration. However, direct comparison of spherical aberration measurements between the Sirius system and other Scheimpflug systems is difficult because the Galilei and Pentacam systems use the wavefront-error approach whereas the Sirius system uses the optical-path-length difference approach to report the measured value. In addition, we evaluated the repeatability of anterior and posterior corneal surfaces separately in the present study, whereas in the study of the Galilei device,[27] spherical aberration was derived from both the anterior and posterior corneal surfaces.

We found that in normal eyes, the repeatability ICCs of the HOAs that represent less complex shapes with lower azimuthal frequencies tended to be better (with ICC values >0.85) than the HOAs, showing more complex corneal shapes with higher azimuthal frequencies (ie, >2) for the anterior corneal surface. Although trefoil $Z(3,\pm3)$, quadrifoil $Z(4,\pm4)$, pentafoil $Z(5,\pm5)$, and secondary trefoil $Z(5,\pm3)$ had lower consistency (ICC $<$ 0.80), the clinical repeatability was acceptable (<0.13 µm). The measurements of normalized polar Zernike coefficients for the anterior corneal surface in keratoconus eyes were good, with ICC values greater than 0.93 except pentafoil, quadrifoil, and secondary trefoil.

Cheng et al.[30] previously suggested that small eye movements may induce variability in aberration measurements in normal subjects. Therefore, it is anticipated that small eye movements would induce larger variations in aberrations in eyes with corneal ectasia and one may expect lower repeatability measurements in pathologic eyes. However, at present, these suggestions remain unexplored. In the current study, the ICCs of anterior and posterior corneal aberrations were mostly higher in keratoconus eyes than in normal eyes. Savini et al.[9] evaluated the repeatability of spherical aberration with the Sirius system and similarly found higher ICCs in eyes after refractive surgery (ICC 0.980) and keratoconus eyes (ICC 0.981) than in normal eyes (ICC 0.806). Although it is difficult to find a satisfactory explanation for this, it is possible that patients with diseased corneas may be generally be more motivated to fixate on the target, which might have played a role in minimizing the effects of small eye movements.

The repeatability ICCs for the BCV_f and BCV_b indices analyzed in this study were excellent (>0.96) in the normal group and the keratoconus group. Clinical repeatability ($2.77 \times S_w$) was lower than 0.12 µm for BCV_f and BCV_b in normal eyes. These findings indicate that the new Scheimpflug–Placido topographer provides dependable BCV_f and BCV_b indices.

Regarding HOAs caused by the posterior corneal surface, the repeatability ICCs were moderate for most aberrations in both groups. Pentafoil $Z(5,\pm5)$ and quadrifoil $Z(4,\pm4)$ were the aberrations with the poorest repeatability ICCs. Piñero et al.[29] found higher test–retest variability values for individual Zernike terms and similar or worse ICCs (range 0.559 to 0.967 for observer 1 and 0.393 to 0.981 for observer 2) in posterior corneal wavefront analysis in normal eyes using Pentacam Scheimpflug imaging. The authors suggest that the reason for poor repeatability might be the inadequate characterization of posterior corneal aberrations with Zernike polynomial expansion or subtle movements during scanning.

With the Sirius system, Zernike coefficients can be analyzed up to the 7th order. The accuracy of Zernike analysis depends on several factors, such as the irregularity of the surface and the number of polynomial terms or orders used to fit the surface. It has been argued that more Zernike terms may be required to accurately characterize the wavefront. However, this may not be practical in a clinical environment and higher-order Zernike terms can occasionally cancel out lower-order Zernike terms and vice versa in unpredictable ways.[28]

In conclusion, the repeatability of the corneal curvature at the 3.0 mm zone and most of the anterior corneal aberrations with the Sirius system were high in normal and keratoconus eyes, whereas this device showed moderate repeatability for the posterior corneal surface and greater variability in pentafoil and quadrifoil aberration measurements.

WHAT WAS KNOWN

- Technology combining a rotating Scheimpflug camera and a Placido disk provides repeatable anterior segment measurements, including pachymetry, corneal curvature, corneal asphericity, anterior chamber depth, and white-to-white distance.

WHAT THIS PAPER ADDS

- The combined technology provided mostly repeatable anterior corneal aberrometry in normal and keratoconus eyes.
- The repeatability of posterior corneal aberration measurements using this technology was moderate except for pentafoil and quadrifoil aberrations.

REFERENCES

1. Oliveira CM, Ferreira A, Franco S. Wavefront analysis and Zernike polynomial decomposition for evaluation of corneal optical quality. J Cataract Refract Surg 2012; 38:343–356
2. Kim A, Chuck RS. Wavefront-guided customized corneal ablation. Curr Opin Ophthalmol 2008; 19:314–320
3. Kermani O, Schmiedt K, Oberheide U, Gerten G. Topographic- and wavefront-guided customized ablations with the NIDEK-EC5000CXII in LASIK for myopia. J Refract Surg 2006; 22:754–763
4. Marsack JD, Parker KE, Applegate RA. Performance of wavefront-guided soft lenses in three keratoconus subjects. Optom Vis Sci 2008; E1172–E1178. Available at: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2614306/pdf/nihms76339.pdf. Accessed September 10, 2013
5. Nochez Y, Favard A, Majzoub S, Pisella P-J. Measurement of corneal aberrations for customisation of intraocular lens asphericity: impact on quality of vision after micro-incision cataract surgery. Br J Ophthalmol 2010; 94:440–444
6. Alió JL, Shabayek HM. Corneal higher order aberrations: a method to grade keratoconus. J Refract Surg 2006; 22:539–545
7. Gobbe M, Guillon M. Corneal wavefront aberration measurements to detect keratoconus patients. Cont Lens Anterior Eye 2005; 28:57–66
8. International Organization for Standardization. Accuracy (Trueness and Precision) of Measurement Methods and Results. Part 1. General Principles and Definitions. Geneva, Switzerland, ISO, 1994; (ISO 5725–1:1994)
9. Savini G, Barboni P, Carbonelli M, Hoffer KJ. Repeatability of automatic measurements by a new Scheimpflug camera combined with Placido topography. J Cataract Refract Surg 2011; 37:1809–1816
10. Montalbán R, Alió JL, Javaloy J, Piñero DP. Intrasubject repeatability in keratoconus-eye measurements obtained with a new Scheimpflug photography-based system. J Cataract Refract Surg 2013; 39:211–218
11. Wang Q, Savini G, Hoffer KJ, Xu Z, Feng Y, Wen D, Hua Y, Yang F, Pan C, Huang J. A comprehensive assessment of the precision and agreement of anterior corneal power measurements obtained using 8 different devices. PLoS One 2012; 7:e45607. Available at: http://www.plosone.org/article/fetchObjectAttachment.action;jsessionid=FA35E04FCB197C7A1C0E3C6B0864525C?uri=info%3Adoi%2F10.1371%2Fjournal.pone.0045607&representation=PDF. Accessed September 10, 2013
12. Rabinowitz YS. Keratoconus. Surv Ophthalmol 1998; 42:297–319. Available at: http://www.keratoconus.com/resources/Major+Review-Keratoconus.pdf. Accessed September 10, 2013
13. Arbelaez MC, Versaci F, Vestri G, Barboni P, Savini G. Use of a support vector machine for keratoconus and subclinical keratoconus detection by topographic and tomographic data. Ophthalmology 2012; 119:2231–2238
14. Zadnik K, Barr JT, Gordon MO, Edrington TB; for the Collaborative Longitudinal Evaluation of Keratoconus (CLEK) Study Group. Biomicroscopic signs and disease severity in keratoconus. Cornea 1996; 15:139–146. Available at: https://vrcc.wustl.edu/clekarchive/pdf/01%20Zandnik%201996%20-%20Biomicrosopic%20Signs.pdf. Accessed September 10, 2013
15. Schwiegerling J, Greivenkamp JE. Keratoconus detection based on videokeratoscopic height data. Optom Vis Sci 1996; 73:721–728. Available at: http://journals.lww.com/optvissci/Abstract/1996/12000/Keratoconus_Detection_Based_on_Videokeratoscopic.1.aspx. Accessed September 10, 2013
16. Li X, Yang H, Rabinowitz YS. Keratoconus: classification scheme based on videokeratography and clinical signs. J Cataract Refract Surg 2009; 35:1597–1603
17. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1:307–310. Available at: http://www-users.york.ac.uk/~mb55/meas/ba.pdf. Accessed September 10, 2013
18. Bland JM, Altman DG. Measurement error and correlation coefficients [Statistics notes]. BMJ 1996; 313:41–42; correction, 744. Available at: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2351452/pdf/bmj00549-0045.pdf. Accessed September 10, 2013. Correction available at: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2352111/pdf/bmj00560-0056b.pdf. Accessed September 10, 2013
19. Applegate RA, Hilmantel G, Howland HC, Tu EY, Starck T, Zayac EJ. Corneal first surface optical aberrations and visual performance. J Refract Surg 2000; 16:507–514
20. Mrochen M, Kaemmerer M, Mierdel P, Seiler T. Increased higher-order optical aberrations after laser refractive surgery; a problem of subclinical decentration. J Cataract Refract Surg 2001; 27:362–369
21. Bühren J, Kühne C, Kohnen T. Defining subclinical keratoconus using corneal first-surface higher-order aberrations. Am J Ophthalmol 2007; 143:381–389
22. Kawamorita T, Uozata H, Kamiya K, Bax L, Tsutsui K, Aizawa D, Shimizu K. Repeatability, reproducibility, and agreement characteristics of rotating Scheimpflug photography and scanning-slit corneal topography for corneal power measurement. J Cataract Refract Surg 2009; 35:127–133
23. McGraw KO, Wong SP. Forming inferences about some intraclass correlation coefficients. Psychol Meth 1996; 1:30–46
24. Artal P, Berrio E, Guirao A, Piers P. Contribution of the cornea and internal surfaces to the change of ocular aberrations with age. J Opt Soc Am A Opt Image Sci Vis 2002; 19:137–143
25. Chen M, Yoon G. Posterior corneal aberrations and their compensation effects on anterior corneal aberrations in keratoconic eyes. Invest Ophthalmol Vis Sci 2008; 49:5645–5652. Available at: http://www.iovs.org/content/49/12/5645.full.pdf. Accessed September 10, 2013
26. Shankar H, Taranath D, Santhirathelagan CT, Pesudovs K. Repeatability of corneal first-surface wavefront aberrations measured with Pentacam corneal topography. J Cataract Refract Surg 2008; 34:727–734
27. Wang L, Shirayama M, Koch DD. Repeatability of corneal power and wavefront aberration measurements with a dual-Scheimpflug placido corneal topographer. J Cataract Refract Surg 2010; 36:425–430
28. Smolek MK, Klyce SD. Zernike polynomial fitting fails to represent all visually significant corneal aberrations. Invest Ophthalmol Vis Sci 2003; 44:4676–4681. Available at: http://www.iovs.org/cgi/reprint/44/11/4676. Accessed September 10, 2013
29. Piñero DP, Saenz González C, Alió JL. Intraobserver and interobserver repeatability of curvature and aberrometric measurements of the posterior corneal surface in normal eyes using Scheimpflug photography. J Cataract Refract Surg 2009; 35:113–120
30. Cheng X, Himebaugh N, Kollbaum PS, Thibos LN, Bradley A. Test-retest reliability of clinical Schack-Hartmann measurements. Invest Ophthalmol Vis Sci 2004; 45:351–360. Available at: http://www.iovs.org/cgi/reprint/45/1/351.pdf. Accessed September 10, 2013

First author:
Hasan Ali Bayhan, MD

Bozok University Medicine Faculty, Ophthalmology Department, Yozgat, Turkey