ARTICLE

# Repeatability of corneal first-surface wavefront aberrations measured with Pentacam corneal topography

Hema Shankar, BMBS, MA, Deepa Taranath, MBBS, MS(Ophthal),
Chandramalar T. Santhirathelagan, MBBS, MMED (Ophthal), Konrad Pesudovs, PhD

**PURPOSE:** To assess the repeatability of corneal wavefront aberrations derived from Pentacam (Oculus) corneal topography.

**SETTING:** Flinders Eye Centre, Flinders Medical Centre, Bedford Park, South Australia, Australia.

**METHODS:** Forty-five normal participants and 10 participants with keratoconus were tested. Intraobserver and interobserver repeatability was determined using 4 observers within and between sessions. Topographical maps were exported to external software, and corneal first-surface wavefront aberrations were calculated using a 10th-order Zernike expansion over a 6.0 mm optical zone. Repeatability was determined with Bland-Altman limits of agreement and expressed as the coefficient of repeatability (COR).

**RESULTS:** Initial data showed high wavefront aberrations in normal participants and poor repeatability. Topographical maps showed extrapolated topography in zones without data acquisition; maps with less than 6.0 mm of complete data were excluded in the final analysis. The mean wavefront aberrations for normal participants remained high, but repeatability improved. The COR relative to the magnitude of wavefront aberrations was high (average 100%) across all modal pairs and orders, although best for total higher-order root mean square. Participants with keratoconus had higher magnitude wavefront aberrations and poorer repeatability but similar COR to average wavefront aberration ratios. Examination of raw elevation data showed poor repeatability.

**CONCLUSIONS:** Wavefront aberrations calculated from Pentacam corneal topography were large in magnitude, and reliability was poor, largely due to variability in corneal elevation data. Intraobserver and interobserver reliability within and between sessions was comparable. The Pentacam was not reliable in measuring corneal wavefront aberrations.

*J Cataract Refract Surg 2008; 34:727–734 © 2008 ASCRS and ESCRS*

The need to accurately quantify higher-order corneal and ocular aberrations has gained importance in step with the advances in refractive surgery.[1–5] In recent years, various imaging devices have been introduced into ophthalmic practice to acquire optical information easily in a clinically accessible format (J.T. Holladay, MD, et al., "Next Generation Technology for the Cataract & Refractive Surgeon," Cataract & Refractive Surgery Today 2005 (January suppl); pages 1–2. Available at: http://www.crstoday.com/PDF%20Articles/0105/PDFs/oculus.pdf. Accessed January 8, 2008).[2] The Oculus Pentacam (Optikgerate) is one such imaging device. It uses Scheimpflug photography to acquire multiple cross-sectional images of the anterior segment of the eye including the posterior surface of the lens (Pentacam Instruction Manual, Oculus).[2] Internal software reconstructs corneal topography (anterior and posterior surface) from height data and provides analyses of corneal pachymetry, corneal wavefront aberrations, lens densitometry, and complete anterior chamber analysis (depth, volume, and angle) (Pentacam Instruction Manual, Oculus). Corneal topography data can also be exported to commercially available software (eg, VOLPro software, v7.08, Sarver and Associates) to recreate topographic maps and generate data regarding corneal wavefront aberrations.

The usefulness of commercially available imaging devices is based on clinical utility, ease of use, and reliability. The ability to reproduce complex corneal shapes with greater precision and accuracy than preexisting technology would be an added advantage,


Published by Elsevier Inc.

0886-3350/08/$—see front matter

doi:10.1016/j.jcrs.2007.11.056

enhancing clinical utility, particularly in regard to refractive procedures.[2] The clinical usefulness of the Pentacam is established in the literature.[2,6–11] Pentacam imaging has been compared with scanning-slit corneal topography (Orbscan),[7,9,12] ultrasound pachymetry,[11] and optical low-coherence reflectometry[6] and has been found to be comparable and interchangeable with other imaging modalities in determining central corneal thickness in eyes with normal corneas[6,7,9,12] and in eyes with keratoconus.[11] The Pentacam has also been found to be comparable to Orbscan and interchangeable within a clinically significant error range when used for anterior chamber depth (ACD) measurements.[8,10] However, the repeatability of corneal wavefront aberration data derived from Pentacam has never been tested to our knowledge.

The purpose of this study was to assess the repeatability of Pentacam measurements of corneal first-surface wavefront aberrations. To this end, intraobserver and interobserver repeatability of corneal wavefront aberrations, determined from corneal topography imaged with the Pentacam, were tested in both normal and diseased (keratoconic) eyes.

## SUBJECTS AND METHODS

### Subjects

This prospective cross-sectional study comprised 2 normal participant populations and 1 keratoconus population. Population 1 consisted of 10 normal individuals (20 eyes). The 10 individuals were tested on 2 separate occasions, and 2 Pentacam measurements were taken of each eye on both occasions by 3 observers. Population 2 consisted of 35 normal individuals (70 eyes) who had single measurement of each eye by 2 observers during a single sitting on the same day. This resulted in 120 comparisons for within-session intraobserver reliability, 240 comparisons for between-session intraobserver reliability, 240 comparisons for within-session interobserver reliability, and 480 comparisons for between-session interobserver reliability. A third population of patients with keratoconus was also tested to complete repeatability testing for normal eyes and diseased eyes.

Accepted for publication November 28, 2007.

From the Department of Ophthalmology, Flinders Medical Centre, Bedford Park, South Australia, Australia.

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

Supported by the National Health and Medical Research Council (Canberra, Australia) Career Development Award 426765 (Dr. Pesudovs).

Corresponding author: Konrad Pesudovs, NH&MRC Centre for Clinical Eye Research, Department of Ophthalmology, Flinders Medical Centre, Bedford Park, South Australia, 5042, Australia. E-mail: konrad.pesudovs@flinders.edu.au.

Ten participants (14 eyes) with keratoconus were measured twice on 1 occasion by 2 observers. This resulted in 56 comparisons for within-session interobserver reliability. The grading of keratoconus was based on keratometric readings and followed the Collaborative Longitudinal Evaluation of Keratoconus study grading system was as follows: mild = less than 45.0 diopters (D); moderate = 45.0 to 52.0 D; severe = more than 52.0 D.[13]

The inclusion criteria for the normal study participants were any individual irrespective of age or ethnicity who had no known corneal pathology. For Population 1, an additional criterion was participant willingness to return on another day for the second set of measurements. Exclusion criteria were preexisting ocular surface pathology, history of eye trauma, contact lens wear, previous refractive surgery, use of eyedrops, inability to fixate on the target, or any other physical or mental impairment that precluded participation in the testing. Participants with cataract or refractive errors were not excluded. Inclusion criteria for the keratoconus group were participants with keratoconus who had not had penetrating keratoplasty in 1 or both eyes and who were willing to be tested.

The participants in the study were recruited on a purely voluntary basis. The full nature of the study was explained to the participants, and their consent was obtained before the study began. Testing was conducted by 4 observers in accordance with the tenets set out in the Declaration of Helsinki. The study was approved by the Flinders Clinical Research Ethics Committee.

### The Pentacam System

The Oculus Pentacam is a noninvasive system for measuring anterior segment topography using Scheimpflug photography.[2,11] The Scheimpflug camera and a monochromatic slit-light source (blue LED at 475 nm) rotate together around the optical axis of the eye (Pentacam Instruction Manual, Oculus). The system rotates 180 degrees in 2 seconds and produces 25 images with 500 measurement points on the front and back of the corneal surface.[2] The elevation data from these images can be combined to form a 3-dimensional reconstruction of the anterior segment. The proprietary software (v1.14r27) uses data from each image plane to reform surface topography in an axial or tangential format (J.T. Holladay, MD, et al., "Next Generation Technology for the Cataract & Refractive Surgeon," Cataract & Refractive Surgery Today 2005 (January suppl), pages 1–2. Available at: http://www.crstoday.com/PDF%20Articles/0105/PDFs/oculus.pdf. Accessed January 8, 2008).[2]

The Pentacam readings were taken as prescribed in the instruction manual. Participants were seated comfortably in a chair with their chin in the chinrest and forehead resting against the forehead strap. They were instructed to keep both eyes open and fixate on the black target in the center of the blue fixation beam that is activated when the instrument is in scan mode. The machine was used in automatic release mode, which means the scan commences as soon as *x*-, *y*-, and *z*-plane alignment criteria are met. This reduces confounding operator-induced unreliability that can occur with manual scanning, which would depend on operator judgment of alignment. Once the machine was aligned, automatic readings were acquired between 4 to 8 seconds post blink as this has been shown to be when the ocular tear film is most stable.[14,15] This was done to rule out tear-film instability as a confounding variable, even though tear film does not affect anterior corneal surface measurements, according to the manufacturer. The participant's eye movement is constantly monitored by a second camera; only measurements with less than 0.6 mm decentration were included. Only scans registering as "OK" on the instrument's "Examination Quality Specification" (signifying that the scan was taken as per the manufacturer's specifications that all the required parameters were satisfied) were used for analysis.

### Testing Methodology

To verify repeatability, 2 readings of each eye were taken by each of the 3 observers in Population 1. This allowed testing for within-session repeatability between measurements for each observer and for repeatability using different observers; that is, intraobserver and interobserver reliability. This procedure was repeated for the same participant on another day by the same 3 observers to test between-session repeatability. To rule out population bias, a second larger group of normal participants (Population 2) was tested on the same day by 4 observers. Each eye was scanned once by 2 of the observers. Data obtained from this population provided additional verification of intraobserver reliability. Population 3 had all keratoconus eyes tested once by 2 observers to test for repeatability in diseased eyes (same-day interobserver reliability).

### Analysis

Corneal elevation and curvature data were exported from Oculus Pentacam to VOLPro software (version 7.08) for calculation of wavefront aberrations. The repeatability of both wavefront aberrations and the raw elevation data were examined. The topographical maps were aligned as recommended in the ANSI Standard for Corneal Topography Systems (ZNSI Z80.23-2007).[16] To look at raw elevation, data were manually extracted along the vertical and horizontal meridia at 1.0 mm intervals up to 4.0 mm from the corneal vertex, yielding 17 elevation locations for comparison. The corneal first-surface wavefront aberrations were calculated as the optical path difference between the chief ray and a general ray refracted at the air–cornea interface (corneal refractive index 1.376).[3] The reference focal length is calculated from the apical radius of the corneal topography exam (J.T. Holladay, MD, et al., "Next Generation Technology for the Cataract & Refractive Surgeon," Cataract & Refractive Surgery Today 2005 (January suppl), pages 1–2).[3] A 10th-order Zernike expansion was used. A 6.0 mm optical zone was chosen, and the pupil center was assumed to be at the corneal vertex. Zernike coefficients generated by VOLPro were exported to an Excel spreadsheet (Microsoft). Modal pairs (vector magnitudes), summaries of orders, and total higher-order aberrations (HOAs) were calculated from individual terms by the root-mean-square (RMS) approach. These data were used for calculation of Bland-Altman limits of agreement for intraobserver and interobserver recordings to quantify the differences between the measurements. The 95% limits of agreement were estimated by mean difference $\pm$1.96 standard deviation of the differences, which provide an interval within which 95% of the differences between measurements are expected to lie.[17] These results are reported as the coefficient of repeatability (COR = $\pm$1.96 standard deviation of the differences).

The matching of populations for age and sex was tested with analysis of variance (ANOVA) with Scheffé post-hoc significance testing and chi-square testing, respectively. A $P$ value less than 0.05 was considered significant. The matching of the groups for severity of wavefront aberrations was tested with ANOVA with Scheffé post-hoc significance testing. Nineteen wavefront aberration metrics were tested; thus, a Bonferroni correction was used to adjust for $\alpha$ inflation; to maintain significance at the $P<.05$ level, a $P$ value of $0.05/19 = 0.003$ was used to judge significance.

## RESULTS

The mean age of the 6 men and 4 women in Population 1 was 39.0 years $\pm$ 5.4 (SD). The mean age of the 16 men and 19 women in Population 2 was 35.5 $\pm$ 14.8 years. The mean age of the 6 women and 4 men in the keratoconus group was 41 $\pm$ 16 years. Of the 14 eyes in that group, 6 had mild keratoconus, 5 had moderate keratoconus, and 3 had severe keratoconus. There was no statistically significant difference between the 3 populations in age ($F_{2,53} = 0.96$, $P>.05$, ANOVA) or sex distribution (chi square = 0.84, $P>.05$).

The mean wavefront aberrations and standard deviations in the 3 populations are shown in Table 1 and Figure 1. The 3 populations were significantly different ($P<.001$) in all wavefront aberration metrics tested except the 9th and 10th Zernike orders. Post-hoc testing showed that the differences were between the keratoconus population and the 2 normal populations. The 2 normal populations were not significantly different in any metric.

Initial data showed high wavefront aberrations for normal participants (mean total higher-order RMS 0.91 $\pm$ 0.34 μm) and poor reliability, even within session intraobserver within $\pm$0.70 μm (Tables 2 and 3). The topographical maps were reviewed to look for explanations for the poor repeatability of data. Some topographical maps generated in VOLPro showed incomplete data. The corresponding Pentacam maps were reviewed and showed complete data beyond the 6.0 mm diameter (Figure 2, *A* and *B*). However, black dots appeared in the areas corresponding to the missing data in the VOLPro maps. On reviewing the Pentacam manual, it became apparent that when incomplete data occur during imaging, the machine extrapolates topographical data to give the appearance of complete topographical maps. All maps in VOLPro were examined by 2 observers, and the maps with incomplete data (less than 6.0 mm) were identified. The exported Pentacam elevation files in these cases were checked, and it was confirmed that data were missing within the central 6.0 mm diameter (denoted by $-1$ in the elevation files). These maps were excluded and the data reanalyzed. Of 380 maps, 28 (5.7%) (20/240, Population 1; 8/140, Population 2) were removed. The mean wavefront aberrations in normal participants remained high (mean total higher-order RMS 0.88 $\pm$ 0.24 μm), but

**Table 1.** Mean wavefront aberrations (modal pairs) for normal and keratoconus populations showing the effect of missing data within the analyzed area.

| | Mean Wavefront Aberration (μm) ± SD | | |
|---|---|---|---|
| | Normal Groups | | Keratoconus Group |
| Parameter | All Eyes | Complete Data Within 6.0 mm Optical Zone | All Eyes |
| Trefoil | 0.258 ± 0.193 | 0.229 ± 0.130 | 1.045 ± 0.665 |
| Coma | 0.656 ± 0.292 | 0.654 ± 0.273 | 2.497 ± 2.353 |
| Tetrafoil | 0.201 ± 0.163 | 0.181 ± 0.125 | 0.565 ± 0.428 |
| 2nd astigmatism | 0.171 ± 0.126 | 0.158 ± 0.092 | 0.731 ± 0.408 |
| Pentafoil | 0.140 ± 0.102 | 0.133 ± 0.088 | 0.294 ± 0.194 |
| 2nd trefoil | 0.099 ± 0.087 | 0.092 ± 0.055 | 0.227 ± 0.177 |
| 2nd coma | 0.129 ± 0.095 | 0.121 ± 0.064 | 0.335 ± 0.288 |
| Hexafoil | 0.068 ± 0.050 | 0.064 ± 0.042 | 0.126 ± 0.086 |
| 2nd tetrafoil | 0.045 ± 0.048 | 0.039 ± 0.025 | 0.118 ± 0.078 |
| 3rd astigmatism | 0.039 ± 0.050 | 0.033 ± 0.020 | 0.140 ± 0.086 |
| Total HO RMS | 0.910 ± 0.339 | 0.875 ± 0.243 | 3.329 ± 2.216 |

HO RMS = higher-order root mean square

repeatability improved (within-session intraobserver ±0.33; between-session intraobserver ±0.33; within-session interobserver ±0.36; between-session interobserver ±0.35 μm). Interobserver data are presented in Table 2 and intraobserver data, in Table 3. They are also represented in graph form as a comparison of interobserver data and intraobserver data within and between days (Figure 3).

The keratoconus participants had higher-magnitude wavefront aberrations (mean total higher-order RMS 3.33 ± 2.22 μm) and poorer repeatability (±1.62 μm) than the normal populations. However, relative to the magnitude of the wavefront aberrations, the COR was comparable to that in the normal population. The COR as a percentage of wavefront aberrations was high across all modal pairs and orders, although best for total higher-order RMS (39%, intraobserver; 40%, interobserver; 49%, keratoconus). The mean COR to mean wavefront aberration ratio was 100% (intraobserver, 40% to 163%; interobserver 40% to 174%) (Figure 4). The ratio for keratoconus was 33% to 176% (Figure 5).

To address the possible cause of the poor repeatability of the calculated wavefront aberrations, the raw elevation data were also examined. Seventeen elevation locations were compared; the mean absolute elevation and COR are shown in Table 4. The COR was better centrally (2 to 5 μm 1.0 mm from the vertex) and poorer peripherally (9 to 16 μm 4.0 mm from the vertex). However, this was mediated by the magnitude of the mean absolute elevation because as a proportion of the mean

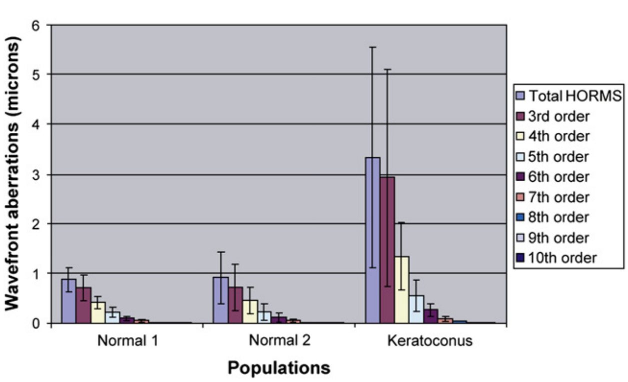


**Figure 1.** Comparison of higher-order wavefront aberrations, by orders, across the 3 populations.

**Table 2.** Interobserver repeatability for normal eyes showing the effect of missing data within the analyzed area.

| | Interobserver Repeatability (COR) | | | |
|---|---|---|---|---|
| | Same Day | | Between Days | |
| Parameter | All Eyes | Complete Data | All Eyes | Complete Data |
| Trefoil | 0.415 | 0.312 | 0.407 | 0.307 |
| Coma | 0.416 | 0.340 | 0.430 | 0.341 |
| Tetrafoil | 0.393 | 0.314 | 0.406 | 0.317 |
| 2nd astigmatism | 0.268 | 0.181 | 0.270 | 0.184 |
| Pentafoil | 0.254 | 0.203 | 0.243 | 0.192 |
| 2nd trefoil | 0.198 | 0.132 | 0.198 | 0.131 |
| 2nd coma | 0.200 | 0.125 | 0.206 | 0.126 |
| Hexafoil | 0.120 | 0.098 | 0.127 | 0.101 |
| 2nd tetrafoil | 0.106 | 0.060 | 0.109 | 0.057 |
| 3rd astigmatism | 0.127 | 0.045 | 0.102 | 0.046 |
| Total HO RMS | 0.599 | 0.356 | 0.608 | 0.347 |

COR = coefficient of repeatability; HO RMS = higher-order root mean square

**Table 3.** Intraobserver repeatability for normal eyes showing the effect of missing data within the analyzed area.

| | Intraobserver Repeatability (COR) | | | |
|---|---|---|---|---|
| | Same Day | | Between Days | |
| Parameter | All Eyes | Complete Data | All Eyes | Complete Data |
| Trefoil | 0.469 | 0.310 | 0.468 | 0.310 |
| Coma | 0.428 | 0.299 | 0.463 | 0.350 |
| Tetrafoil | 0.409 | 0.305 | 0.436 | 0.316 |
| 2nd astigmatism | 0.291 | 0.194 | 0.304 | 0.190 |
| Pentafoil | 0.242 | 0.195 | 0.258 | 0.206 |
| 2nd trefoil | 0.187 | 0.129 | 0.231 | 0.138 |
| 2nd coma | 0.175 | 0.114 | 0.236 | 0.138 |
| Hexafoil | 0.125 | 0.098 | 0.132 | 0.111 |
| 2nd tetrafoil | 0.112 | 0.065 | 0.133 | 0.062 |
| 3rd astigmatism | 0.111 | 0.046 | 0.138 | 0.047 |
| Total HO RMS | 0.696 | 0.326 | 0.754 | 0.350 |

COR = coefficient of repeatability; HO RMS = higher-order root mean square

elevation, COR was greater at 1.0 mm (approximately 5%) than at 2.0 to 4.0 mm (approximately 2%).

## DISCUSSION

One purported advantage of Scheimpflug imaging and the Pentacam system is that slit images are acquired by the Scheimpflug camera on an angle of 0 to 180 degrees, thus avoiding nasal shadowing (Pentacam Instruction Manual, Oculus).[2] In this study, we found that complete data in Pentacam topography maps did not correspond to complete data exported for analysis (Figure 2, *A* and *B*). The data in the VOLPro maps were incomplete superiorly and nasally, suggestive of lid or nasal obstruction as seen in Placido-disk topographers.[18] The corresponding "complete" Pentacam maps were an extrapolated fictional representation as the elevation data acquired during imaging were incomplete. There was no indication during image acquisition that the height data were incomplete as the scans registered as being "OK." The extrapolated data were simply presented as a dotted area on seemingly complete topographical maps. This is misleading and receives limited explanation in the instruction manual. We recommend that this instrument-specific problem be addressed by the manufacturer.

Even using the available complete data only, reliability was poor in the normal and keratoconus groups. Intraobserver and interobserver reliability within session and between sessions was comparable. The ratio of COR to the magnitude of the mean wavefront aberrations was slightly better for intraobserver data but comparable for intraobserver and interobserver data.

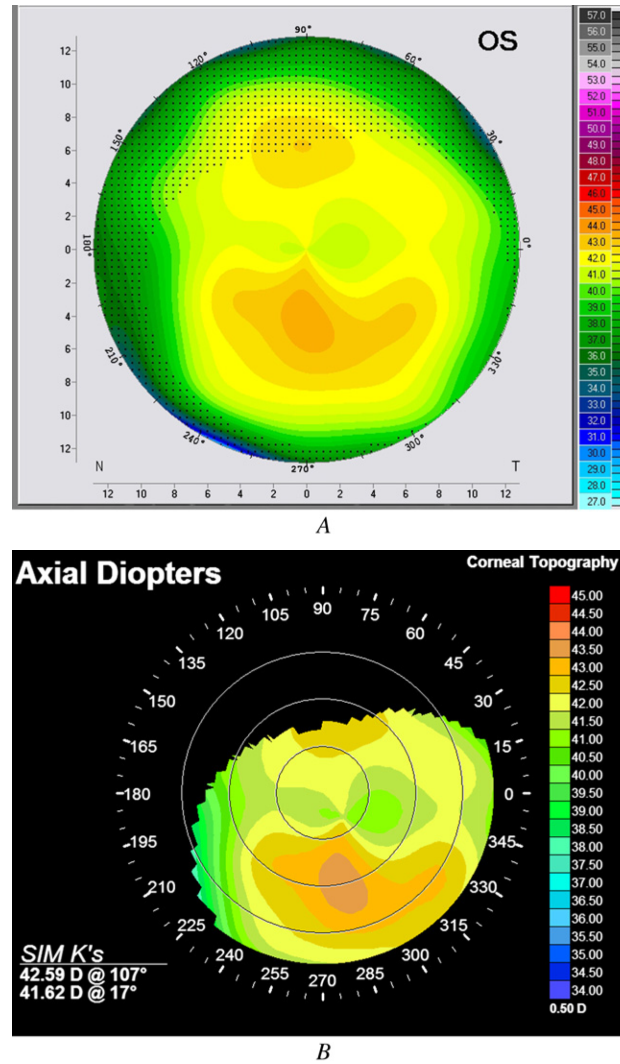


**Figure 2.** *A*: Topographic map generated by the Pentacam showing data out to 12.0 mm. *B*: Topographic map generated by VOLPro for the same patient showing incomplete data with the central 6.0 mm (rings are 3.0 mm, 6.0 mm, and 9.0 mm in diameter).

The comparability of intraobserver and interobserver reliability is not surprising and is due in part to the use of automated capture during image acquisition. The machine was used in automatic-release mode, which minimizes operator differences in relation to judging when the Pentacam is aligned with the patient. Overall, the ratios were unacceptably high, indicating poor reliability. Poor reliability was particularly evident for the individual-mode HOAs of greater magnitude.

The magnitude of aberrations in the normal populations was also surprisingly large. In a previous study using Orbscan corneal topography data from normal eyes exported to VOLPro,[19] the total mean higher-order RMS calculated for a 6.0 mm optical zone was 0.38 ± 0.07 μm. In this study, the magnitude of total

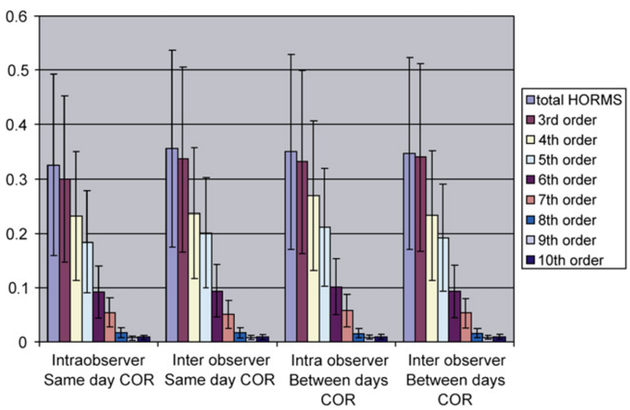


**Figure 3.** Comparison of normal eye intraobserver COR and interobserver COR for same-day and between-day conditions. This analysis includes only cases with complete data for a 6.0 mm optical zone and are reported across orders 3 to 10.

higher-order RMS was more than twice as high at 0.88 $\pm$ 0.24 μm. This high magnitude of wavefront aberrations was seen across all Zernike modes and orders. Although the magnitude of aberrations decreased with increasing Zernike order, as is typical of that seen in human eyes, the absolute magnitude remained high for all coefficients compared with previously published data.[20] The aberrations in the keratoconus groups were also high compared with previously published results, although certain specification of this is confounded by disease severity.[21] The wavefront aberrations were significantly higher in keratoconus eyes than in normal eyes except at the highest orders tested. Ninth- and 10th-order coefficients represent unusual waveforms rarely seen in the human eye so are not of sufficient magnitude to allow detection of differences, even between normal and keratoconus populations. Indeed, the capability of the Pentacam to measure higher-frequency aberrations is

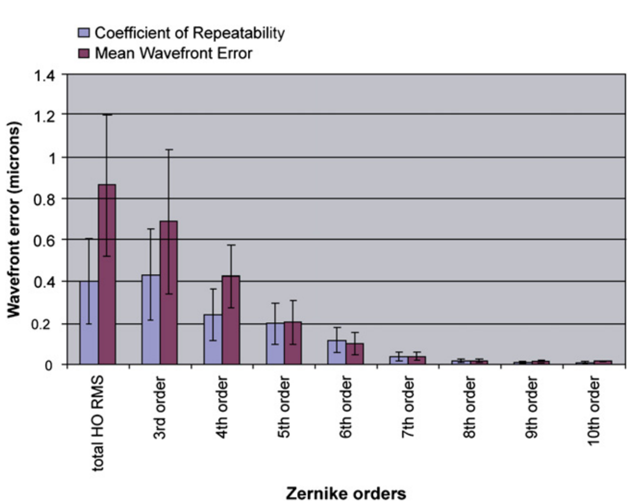


**Figure 4.** Coefficient of repeatability compared to mean wavefront aberrations across all orders in normal Population 2.

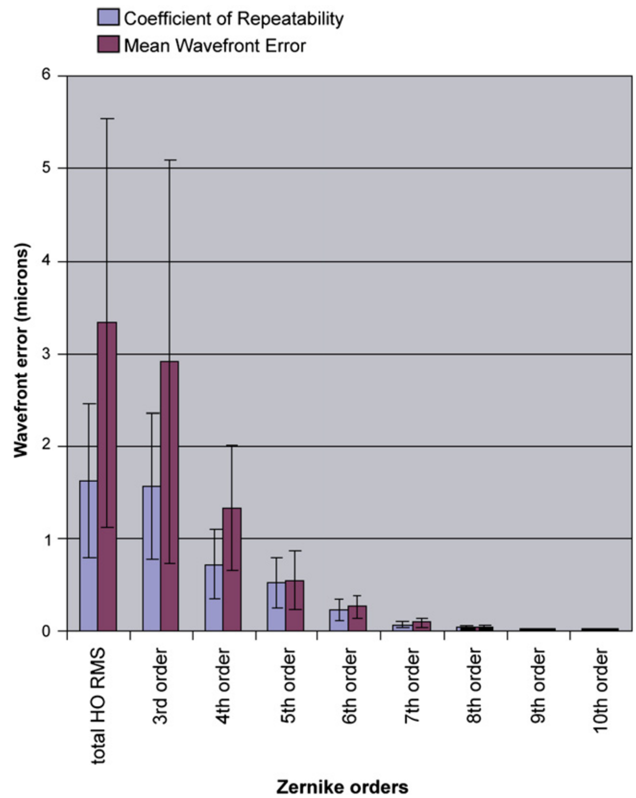


**Figure 5.** Coefficient of repeatability compared to mean wavefront aberrations across all orders in the keratoconus population.

limited by the sampling of only 50 points around the corneal circumference.

To evaluate the cause of the poor repeatability of corneal first-surface wavefront aberrations, we tested the repeatability of raw corneal elevation data. Despite aligning topographies, the elevation repeatability was poor, especially in the peripheral cornea. The COR was of the order of 2 to 5 μm 1.0 mm from the vertex to 9 to 16 μm 4.0 mm from the vertex. This instability of corneal-height measurement would cause a large range of disagreement of wavefront aberration values calculated from these height data. Because the topographies were aligned, the likely cause of this poor repeatability is that the surface measurement was affected by movement during the scan. It has been postulated that coma coefficients display poor repeatability due to fixation and positioning errors between examinations.[22] Patient misalignment may account for some of the changes in aberrations in our study as even slight changes in position will result in a change in aberrations. Guirao et al.[23] showed that HOAs increase with misalignment. This finding is supported in a study by Davies et al.[24] that showed that 49% of Zernike coefficients were different with careful alignment; this figure climbed to 59% when care was not taken to ensure perfect alignment. The authors recommend the

**Table 4.** Mean values and interobserver repeatability of raw elevation data in normal eyes.

| Location | Mean Elevation ± SD (μm) | COR (μm) |
|---|---|---|
| Corneal vertex | 0.000 ± 0.000 | 0.000 |
| 1.0 mm superior | 63.93 ± 2.02 | 3.02 |
| 1.0 mm right | 63.35 ± 2.53 | 5.23 |
| 1.0 mm inferior | 64.25 ± 2.06 | 3.28 |
| 1.0 mm left | 63.30 ± 1.80 | 2.15 |
| 2.0 mm superior | 259.53 ± 6.65 | 6.41 |
| 2.0 mm right | 257.35 ± 6.46 | 4.68 |
| 2.0 mm inferior | 261.50 ± 6.99 | 6.44 |
| 2.0 mm left | 257.18 ± 6.18 | 3.76 |
| 3.0 mm superior | 597.18 ± 15.85 | 14.02 |
| 3.0 mm right | 591.25 ± 14.69 | 7.58 |
| 3.0 mm inferior | 600.05 ± 15.05 | 10.29 |
| 3.0 mm left | 590.55 ± 14.19 | 6.76 |
| 4.0 mm superior | 1091.47 ± 26.90 | 14.33 |
| 4.0 mm right | 1078.18 ± 28.20 | 16.48 |
| 4.0 mm inferior | 1093.90 ± 25.55 | 16.11 |
| 4.0 mm left | 1074.05 ± 26.38 | 9.40 |

COR = coefficient of repeatability

use of a dental bite bar to achieve steadier fixation than can be achieved with a chin rest and forehead strap. The 2 seconds taken for image acquisition with the Pentacam allow for slight shifts and misalignment, even in measurements considered acceptable to the Pentacam's quality specification, as well as short-term variations in ocular aberrations that would cumulatively contribute to poor repeatability.[25] Similarly, in a related study,[26] we found that significant alterations in pupil size during the 2-second scan can markedly affect the repeatability of measures that depend on pupil center or diameter (eg, anterior chamber volume and central corneal thickness).

The reasons for increased magnitude of corneal first-surface wavefront aberrations are not immediately apparent and are possibly multifactorial. One possible explanation is that the function used to extrapolate between the limited number of corneal slices, especially peripherally where the space between samples is widest, induces noise that is misfit as aberration. Also, because the method of calculating wavefront aberrations from corneal height data involves 2 lots of differential calculus,[3] noise in the initial measurement is amplified during each differentiation. This would cause spurious elevation in the magnitude and reliability of the reported corneal first-surface wavefront aberrations. Previous studies[27] found that aberrometry is limited by measurement noise, and this explanation becomes plausible given that the magnitude of total higher-order RMS was more than twice as high in this study.

There is a paucity of data on the repeatability of corneal wavefront aberrations specifically. Gobbe et al.[22] tested repeatability of corneal wavefront aberrations derived from Keratron corneal topography. They found poor repeatability for 5th- to 10th-order coefficients (ratio of COR to magnitude of wavefront aberration 100% to 234%). They reported that while repeatability was poor for individual Zernike coefficients, relative repeatability for total higher-order RMS was good (COR 0.1004 and ratio of COR to magnitude of wavefront aberration of 31% for a 6.0 mm optical zone). We found a similar pattern of poorer repeatability for Zernike modes; repeatability was slightly better when combined into orders and best for total higher-order RMS, although the repeatability of Pentacam-derived wavefront aberrations must be considered to be poor. Recently Holzer et al.[28] found good reliability when testing for measurement of corneal wavefront errors (3rd-order COR 0.15, 4th-order COR 0.12 for a 6.0 mm optical zone) using the Schwind Corneal Wavefront Analyzer (a Placido-disk system). They also found that whole eye wavefront measurement using a Shack-Hartmann system showed better reliability than corneal wavefront measurements.[28] Several other studies[24,25,27,29–31] have analyzed the repeatability of static measurements of whole eye wavefront aberrations. Cheng et al.[25] also found good reliability using a Shack-Hartmann aberrometer (COR 0.035 using 6.0 mm pupil). However, other studies[24,31] report poor repeatability of whole eye HOAs.

The Pentacam does not show reliability of wavefront aberrations calculated from its corneal shape data; therefore, its use is not recommended in assessing and evaluating ocular aberrations. Pentacam software does generate Zernike coefficients, but not in a form that is exportable for analysis. The data acquired were incomplete, and further manual analysis of topographical maps was required. The utility and ease of use of this instrument in assessing wavefront aberrations is questionable. Repeatability was particularly poor in the keratoconus population, demonstrating poor reliability in diseased eyes. The repeatability in normal eyes, although better than in diseased eyes, was still not reliable enough for clinical utility in planning refractive procedures. Theoretically, this could be improved through the averaging of several measurements. Further studies are needed to test the practicality of averaging measurements and the implications for reliability.

This is not to say that the Pentacam does not have clinical uses. As discussed earlier, the Pentacam has been found to be comparable and interchangeable with other imaging modalities in measuring ACD[8,10] and central corneal thickness.[6,7,9,12] Rabsilber et al.[10] recently pointed out that although they found the Pentacam to be reliable in measuring ACD, there was a need for further clinical studies to investigate the accuracy of other Pentacam measurements. The current study demonstrates the poor reliability of Pentacam measurement of wavefront aberrations. Further studies are needed to establish the reliability of other parameters (eg, corneal power, keratometric measurements, anterior chamber angle) measured using the Pentacam. We also analyzed the data collected in this study to further test the reliability of the Pentacam in measuring other parameters.[26]

## REFERENCES


1. Ginis HS, Plainis S, Pallikaris A. Variability of wavefront aberration measurements in small pupil sizes using a clinical Shack-Hartmann aberrometer. BMC Ophthalmol 2004; 4:1. Available at: http://www.biomedcentral.com/1471-2415/4/1. Accessed January 8, 2008
2. Wang M, ed, Corneal topography in the Wavefront Era; a Guide for Clinical Application. Thorofare, NJ, Slack, 2006
3. Guirao A, Artal P. Corneal wave aberration from videokeratography: accuracy and limitations of the procedure. J Opt Soc Am A Opt Image Sci Vis 2000; 17:955–965
4. Ginis HS, Pallikaris I. Overestimation of the spherical aberration after laser refractive surgery. J Cataract Refract Surg 2006; 32:898–899
5. Pesudovs K, Garamendi E, Elliott DB. The Quality of Life Impact of Refractive Correction (QIRC) questionnaire: development and validation. Optom Vis Sci 2004; 81:769–777
6. Barkana Y, Gerber Y, Elbaz U, et al. Central corneal thickness measurement with the Pentacam Scheimpflug system, optical low-coherence reflectometry pachymeter, and ultrasound pachymetry. J Cataract Refract Surg 2005; 31:1729–1735
7. Lackner B, Schmidinger G, Pieh S, et al. Repeatability and reproducibility of central corneal thickness measurement with Pentacam, Orbscan, and ultrasound. Optom Vis Sci 2005; 82: 892–899
8. Lackner B, Schmidinger G, Skorpik C. Validity and repeatability of anterior chamber depth measurements with Pentacam and Orbscan. Optom Vis Sci 2005; 82:858–861
9. O'Donnell C, Maldonado-Codina C. Agreement and repeatability of central thickness measurement in normal corneas using ultrasound pachymetry and the OCULUS Pentacam. Cornea 2005; 24:920–924
10. Rabsilber TM, Khoramnia R, Auffarth GU. Anterior chamber measurements using Pentacam rotating Scheimpflug camera. J Cataract Refract Surg 2006; 32:456–459
11. Uçakhan ÖÖ, Özkan M, Kanpolat A. Corneal thickness measurements in normal and keratoconic eyes: Pentacam comprehensive eye scanner versus noncontact specular microscopy and ultrasound pachymetry. J Cataract Refract Surg 2006; 32:970–977
12. Amano S, Honda N, Amano Y, et al. Comparison of central corneal thickness measurements by rotating Scheimpflug camera, ultrasonic pachymetry, and scanning-slit corneal topography. Ophthalmology 2006; 113:937–941
13. Zadnik K, Barr JT, Edrington TB, et al. Baseline findings in the Collaborative Longitudinal Evaluation of Keratoconus (CLEK) Study. Invest Ophthalmol Vis Sci 1998; 39:2537–2546. Available at: http://www.iovs.org/cgi/reprint/39/13/2537. Accessed January 8, 2008
14. Montés-Micó R, Alió JL, Muñoz G, et al. Postblink changes in total and corneal ocular aberrations. Ophthalmology 2004; 111:758–767
15. Koh S, Maeda N, Hirohara Y, et al. Serial measurements of higher-order aberrations after blinking in normal subjects. Invest Ophthalmol Vis Sci 2006; 47:3318–3324. Available at: http://www.iovs.org/cgi/reprint/47/8/3318. Accessed January 8, 2008
16. American National Standards Institute, Inc. American National Standard for Ophthalmics - Corneal Topography Systems - Standard Terminology, Requirements. ANSI Z80.23–2007
17. Bland JM, Altman DG. Measuring agreement in method comparison studies. Stat Methods Med Res 1999; 8:135–160
18. Dave T, Ruston D, Fowler C. Evaluation of the EyeSys model II computerized videokeratoscope. Part I. Clinical assessment. Optom Vis Sci 1998; 75:647–655
19. Pesudovs K. Wavefront aberration outcomes of LASIK for high myopia and high hyperopia. J Refract Surg 2005; 21:S508–S512
20. Williams DR, Porter J, Yoon G, et al. How far can we extend the limits of human vision? In: Krueger RR, Applegate RA, MacRae SM, eds, Wavefront Customized Visual Correction: the Quest for Super Vision II. Thorofare, NJ, Slack, 2004; 19–38
21. Shah S, Naroo S, Hosking S, et al. Nidek OPD-scan analysis of normal, keratoconic, and penetrating keratoplasty eyes. J Refract Surg 2003; 19:S255–S259
22. Gobbe M, Guillon M, Maissa C. Measurement repeatability of corneal aberrations. J Refract Surg 2002; 18:S567–S571
23. Guirao A, Williams DR, Cox IG. Effect of rotation and translation on the expected benefit of an ideal method to correct the eye's higher-order aberrations. J Opt Soc Am A Opt Image Sci Vis 2001; 18:1003–1015
24. Davies N, Diaz-Santana L, Lara-Saucedo D. Repeatability of ocular wavefront measurement. Optom Vis Sci 2003; 80:142–150
25. Cheng X, Himebaugh NL, Kolbaum PS, et al. Test-retest reliability of clinical Shack-Hartmann measurements. Invest Ophthalmol Vis Sci 2004; 45:351–360. Available at: http://www.iovs.org/cgi/reprint/45/1/351.pdf. Accessed January 8, 2008
26. Shankar H, Taranath D, Santhirathelagan CT, Pesudovs K. Anterior segment biometry with the Pentacam: comprehensive assessment of repeatability of automated measurements. J Cataract Refract Surg 2008; 34:103–113
27. Rodríguez P, Navarro R, González L, Hernández JL. Accuracy and reproducibility of Zywave, Tracey, and experimental aberrometers. J Refract Surg 2004; 20:810–817
28. Holzer MP, Sassenroth M, Auffarth GU. Reliability of corneal and total wavefront aberration measurements with the SCHWIND Corneal and Ocular Wavefront Analyzers. J Refract Surg 2006; 22:917–920
29. Prieto PM, Vargas-Martín F, Goelz S, Artal P. Analysis of the performance of the Hartmann-Shack sensor in the human eye. J Opt Soc Am A Opt Image Sci Vis 2000; 17:1388–1398
30. Salmon TO, Thibos LN, Bradley A. Comparison of the eye's wave-front aberration measured psychophysically and with the Shack-Hartmann wave-front sensor. J Opt Soc Am A Opt Image Sci Vis 1998; 15:2457–2465
31. Zadok D, Levy Y, Segal O, et al. Ocular higher-order aberrations in myopia and skiascopic wavefront repeatability. J Cataract Refract Surg 2005; 31:1128–1132


First author:
Hema Shankar, BMBS, MA

*Department of Ophthalmology, Flinders Medical Centre, Bedford Park, South Australia, Australia*