ARTICLE

Anterior segment biometry with the Pentacam: Comprehensive assessment of repeatability of automated measurements

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PURPOSE: To comprehensively assess the reliability of automated Pentacam (Oculus, Inc.) measurements.

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

METHODS: Both eyes of 35 normal volunteers were tested twice on the same day by 2 different observers. All automated values were recorded, and manual analysis of topographic maps was performed only to overrule variance in corneal thickness due to pupil decentration altering the central reference point. Repeatability was determined with Bland-Altman limits of agreement and reported as the coefficient of repeatability (COR = $\pm$1.96 standard deviation of differences). Relative repeatability (RR) was calculated as a percentage of the ratio of COR to the mean.

RESULTS: Overall, repeatability was good. Corneal curvature, reported in diopters, showed good repeatability anteriorly (simulated keratometry mean COR$\pm$0.28D; RR=0.64%) and posteriorly (COR$\pm$011D; RR=1.85%). Peripheral corneal curvature was more reliable when calculated by the sagittal (axial) method (RR=1.57%) than by the tangential (meridional) method (RR=2.38%). Keratometric power deviation was less reliable (RR=16.39%). Anterior chamber measurements showed good reliability (RR=3.07%-5.68%) except for anterior chamber angle (RR=14.41%). Pupil diameter showed poor reliability (RR=25.77%). Central corneal thickness was comparable at pupil center and corneal vertex, but peripheral repeatability was much better when centered on the corneal vertex (COR$\pm$16.00μm; RR=2.56%) than at pupil center (COR$\pm$26.28μm; RR=4.23%).

CONCLUSIONS: Pentacam corneal curvature and anterior chamber parameters were highly repeatable, but pupil measurements had poor repeatability. Peripheral pachymetry readings were affected by pupil decentration and required manual analysis using the corneal vertex as the point of reference to achieve good repeatability.

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The Pentacam (Oculus, Inc.) imaging device has been operational in ophthalmic practice since it was approved for use in the United States in 2004.[1] The usefulness of Pentacam is extolled in the promotional literature (J.T. Holladay, MD, et al., "Next-Generation Technology for the Cataract & Refractive Surgeon," Cataract & Refractive Surgery Today January 2005 (suppl). Available at http://www.crstoday.com/PDF%20Articles/0105/PDFs/oculus.pdf. Accessed October 10, 2007; Pentacam Instruction Manual. Oculus; B. Dick, MD, et al., "Interpretation of Scheimpflug Based Anterior Segment Imaging and Mapping." Eurotimes 2005; 10:51–56. Available at: http://www.oculus.de/en/downloads/dyn/sonstige/sonstige/2_eye_eye_supplement.pdf. Accessed October 10, 2007; M.W. Belin, MD, et al., "The Pentacam: Precision, Confidence, Results, and Accurate "Ks!" Cataract & Refractive Surgery Today 2007. Available at: http://www.crstoday.com/PDF%20Articles/0107/0107_supp_oculus.pdf. Accessed October 10, 2007).

The Pentacam is touted as a multifunctional imaging device—a "comprehensive eye scanner for the anterior eye segment"—by the manufacturer (Pentacam Instruction Manual, Oculus, Inc.). But how useful is the Pentacam as a clinical tool? We set out to answer this question by quantifying the reliability of all Pentacam measurements. Only central corneal thickness

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(CCT) and anterior chamber depth (ACD) measurements have been rigorously tested for reliability.[2–13] Several studies report that the Pentacam has excellent reliability in measuring CCT[2–9] and ACD[9–13] in normal and keratoconus populations.[6] The repeatability of posterior corneal elevation was also reported in a recent publication.[14] In contradiction to previous findings of excellent repeatability, we found poor repeatability of wavefront aberrations derived from Pentacam corneal topography in an independent study (H. Shankar, et al., personal communication). This highlighted the fact that many Pentacam measurements remain unstudied to date, although the machine is widely in use and rapidly gaining acceptance as a necessary clinical tool (Holladay and Belin references above).

Many diagnostic imaging tools are available for ophthalmic practice, and there is much overlap of functionality between devices. For example, in our setting, we have 3 different imaging devices to measure CCT, 2 to measure wavefront aberrations, and 3 to measure corneal shape, as well as several manual measuring devices. Although there is a glut of automated ophthalmic imaging devices, there is a corresponding dearth of independent studies verifying the manufacturers' claims of clinical utility. Studies aimed at objectively quantifying reliability and ease of use and identifying the strengths and drawbacks of these imaging modalities are necessary and would aid clinical decision making, facilitating efficient and cost effective testing while minimizing redundancy and reducing patient discomfort by potentially reducing the number of required tests.

In this prospective study, we comprehensively assessed interobserver reliability of different parameters (corneal curvature, anterior chamber measurements, pupil dimensions, and corneal pachymetry) automatically measured by the Pentacam system. We reviewed the topographical maps of a group of normal participants to verify the reliability of the Pentacam device and establish its usefulness as a clinical tool.

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SUBJECTS AND METHODS

Thirty-five normal volunteers were recruited for testing. Seventy eyes were tested. The analysis involved 67 eyes as 3 eyes were excluded because the scans did not register as "OK" on the instrument's Examination Quality Specification, which signifies whether the scan satisfied a series of parameters (eg, movement, decentration, missing segments). During testing, repeat measurement was performed when scanning failed the quality specification; however, in these 3 eyes, "OK" scans were not obtained.

Inclusion criteria were any individual irrespective of age or ethnicity with no known ocular pathology. Participants with cataract or refractive error were not excluded. 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 other physical or mental impairment that precluded participation in the testing.

Testing was conducted by 4 observers (K.P., D.T., C.S., H.S.) in accordance with the principles concerning research involving human subjects set out in the Declaration of Helsinki. The full nature of the study was explained to participants, and consent was obtained before proceeding with the testing. Both eyes of each participant were scanned once by 2 different observers during a single sitting. The participant remained seated between measurements but was repositioned in the headrest for each measurement. All participants were tested on the same day between 10:00 AM and 4:00 PM after they had been awake at least 3 to 4 hours.[15] Testing took place with natural pupils and under the same conditions in ambient (entirely artificial) lighting. Participants were seated comfortably, and alignment was achieved using the table height adjustment, forehead strap, and chin rest. Participants were instructed to keep both eyes open and look directly at the black fixation target centered in the scanning-slit light for the duration of the scan (2 seconds). The machine was used in automatic release mode to rule out confounding operator-related variables.

The Pentacam System

The Pentacam uses Scheimpflug imaging to acquire multiple photographs of the anterior segment of the eye[16] (Pentacam instruction manual). It is a noninvasive system that uses a monochromatic slit-light source (blue LED at 475 nm) for measuring anterior segment topography. Twenty-five images with 500 measurement points on the front and the back of the corneal surface are acquired over a 180-degree rotation in 2 seconds. Internal software (v1.14r27) uses the elevation data from these images to form a 3-dimensional reconstruction of the anterior segment as well as creation of axial and meridional corneal topography maps[16] (J.T. Holladay, MD, et al. "Next-Generation Technology for the Cataract & Refractive Surgeon," Cataract & Refractive Surgery Today January 2005(suppl). Available at http://www.crstoday.com/PDF%20Articles/0105/PDFs/oculus.pdf. Accessed October 10, 2007; Pentacam instruction manual).

Measurements

Corneal Curvature The Pentacam measures the corneal curvature at both the anterior and posterior surfaces. Corneal curvature is measured from limbus to limbus (in an ideal scenario) and is automatically reported in concentric rings of 1.0 mm increments. The reported values within each ring reflect the proportion of the total area represented by each ring (B. Dick, MD, et al, "Interpretation of Scheimpflug Based Anterior Segment Imaging and Mapping. Eurotimes 2005; 10:51–56. Available at: http://www.oculus.de/en/downloads/dyn/sonstige/sonstige/2_eye_eye_supplement.pdf. Accessed October 10, 2007). Corneal curvature can still be measured at any point on the cornea by manually placing the cursor over that point. Corneal curvature is calculated centered on the corneal vertex using different refractive indices for different topographical output. Curvature can be reported in millimeters or diopters. Dioptric power maps are produced by converting the radius of curvature into diopters using various refractive indices. Traditional anterior surface power maps, axial or meridional, are produced using the keratometric refractive index ($n = 1.3375$). Posterior corneal topography is calculated using the true refractive indices for the tissue–fluid interface (1.376 for cornea and 1.336 for aqueous). In this study, corneal curvature was calculated by the axial method (in which radius of curvature is calculated from the surface to the corneal topographer axis along the corneal meridian normal at that point) and the meridional method (local surface curvature measured in the meridional plane: the curvature of the corneal meridian at the surface point).[17] The Pentacam uses the terms *sagittal curvature* and *tangential curvature* to describe axial curvature and meridional curvature, respectively. Although numerous other devices have used this terminology,[18] the current ANSI standard for corneal topographers (ANSI Z80.23-2007) recommends the terms *axial curvature* and *meridional curvature*.[17] To minimize confusion for those attempting to correlate the findings in this study to their Pentacam, both terms are used in this paper.

The Pentacam also produces a true net power map, which is purported to be a report of total corneal power. This is calculated using the thick lens formula incorporating true refractive indices (air = 1.0, cornea = 1.376, and aqueous = 1.336) at each interface (Pentacam instruction manual). The true net power assumes that the expression of surface curvature in units of diopters represents corneal power, and the anterior and posterior surface curvatures can be combined in the thick lens formula (which also includes the corneal thickness) to calculate the overall power of the cornea as a "thick lens." These are not genuine power maps but rather are curvature maps reported in units of dioptric power. Although this is a standard approach for corneal topography output, the use of the term *corneal power* should not imply that ray tracing was performed or refraction calculated.

Corneal curvature is reported by a series of metrics: K1 represents the corneal curvature in the flat central 3.0 mm zone, K2 represents the steep central radius in the 3.0 mm zone, and Km is the average of K1 and K2 (Pentacam instruction manual). These are analogous to traditional keratometry readings (K readings) but are produced for the posterior surface also. The repeatability of the 6 peripheral anterior corneal curvature measurements in the 4.0 mm zone were also tested. These are represented by K^1 through K^6, with K^1 being the measurement recorded at the 12 o'clock position and the consecutive readings spaced by 60 degrees in the clockwise direction on the topographical map. These 6 peripheral curvatures are reported for both sagittal (axial) and tangential (meridional) maps.

Keratometric Power Deviation Keratometric power deviation (KPD) is the difference between anterior corneal curvature in diopters at any given point on the sagittal (axial) curvature map and the true net power (Pentacam instruction manual). This reports the difference between the traditional corneal topography maps calculated using the keratometric refractive index ($n = 1.3375$) of the air–anterior corneal interface only and a total corneal power calculated from the curvature of both the anterior and posterior corneal surfaces using the true refractive indices (air = 1.000, cornea = 1.376, aqueous = 1.333). The area of cornea used to calculate KPD is in the 0.8 mm to 1.6 mm diameter around the corneal vertex. The KPD value used in the analysis was the single KPD result appearing in the summary data found on the color map page. The validity of KPD as a measure is marred by the assumption that the reporting of corneal surface curvature in units of diopters is equivalent to corneal power. The same can be said of true net power. Nevertheless, as a standard Pentacam output, the reliability of these 2 measures was tested in keeping with the aims of this study.

Pupil Pupil diameter was averaged over the duration of the scan, and the value that appears in the output is the mean diameter of the pupil. The x and y Cartesian coordinates give the horizontal and vertical positions of the pupil center in relation to the corneal vertex.

Corneal Thickness Corneal thickness is available for the entire cornea, limbus to limbus, although data are often not available for the full surface. It is automatically reported in concentric circles (of 1.0 mm increments), although corneal thickness can still be measured at any point on the cornea by manually placing the cursor at that point. The default standard is to report pachymetry using the pupil center as the reference point. Pachymetry superior (called peripheral 1 here) gives the thickness of the cornea 3.0 mm above the pupil center. Pachymetry temporal (peripheral 2) gives corneal thickness 3.0 mm from the pupil center temporally. Pachymetry inferior (peripheral 3) gives thickness 3.0 mm below the pupil center. Pachymetry nasal (peripheral 4) gives thickness 3.0 mm toward the nose from the pupil center (Pentacam instruction manual).

The Pentacam maps were reviewed by 2 observers, and a second manual analysis was undertaken in an attempt to improve the repeatability of corneal thickness measurements. Using the gridlines provided with the maps, corneal thickness was calculated with the corneal vertex as the point of reference. Corneal thickness was measured manually at 4 corresponding points, 3.00 mm from the corneal vertex, allowing 0.02 mm on either the x or y axis for decentration, with peripheral 1 denoting corneal thickness 3.0 mm superior to the corneal vertex, peripheral 2 representing corneal thickness 3.0 mm temporal to the vertex, peripheral 3 being 3.0 mm inferior to the corneal vertex, and peripheral 4 representing 3.0 mm nasal to the corneal vertex.

Central corneal thickness is reported for the pupil center and the corneal vertex.

Corneal Volume A 10.0 mm diameter around the corneal vertex and anterior and posterior corneal surfaces defines the boundaries for the calculation of corneal volume (Pentacam instruction manual).

Anterior Chamber

Volume Integral calculus is used to calculate anterior chamber volume as a solid bounded by the posterior surface of the cornea (12.0 mm around the corneal vertex) and the iris and lens (Pentacam instruction manual).

Depth Anterior chamber depth is calculated from the corneal endothelium in line with the corneal vertex to the anterior surface of the lens. Anterior chamber depth can also be calculated from the corneal epithelium by changing the settings on the machine.

Angle The default anterior chamber angle given in the topographic map is the smaller of the 2 angles taken in the horizontal section. Machine settings can be changed to display the superior, inferior, temporal, or nasal angle measurement.

Statistical Analysis

Data for different parameters measured by Pentacam were gathered from the topographical maps generated and entered into an Excel spreadsheet. Agreement between readings taken by the 2 observers were calculated for each eye of each participant using Bland-Altman limits of agreement.[19] The 95% limits of agreement were estimated by mean difference ± 1.96 standard deviation of the differences which provides an interval within which 95% of the differences between measurements are expected to lie.[19] These results are reported as the coefficient of repeatability (COR ± 1.96 standard deviation of the differences). Since limits of agreement can sometimes be difficult to interpret clinically, repeatability was also put into context of the absolute value of measurement using relative repeatability (RR). Relative repeatability was calculated as a percentage of the ratio of COR to the mean value of the measure. This gives a clear idea of the reliability of a measure and allows comparison of repeatability across different types of measurements.

RESULTS

The mean age of the participants was 35.5 years $\pm$ 14.8 (SD) (range 7 to 65 years). Sixteen participants were men. Patient demographics are represented graphically in Figure 1.

Corneal Curvature

The mean K reading for the corneal front surface at the vertex was 42.98 $\pm$ 1.27 diopters (D), and the mean difference was 0.00 $\pm$ 0.14 D. The mean K reading for the back surface at the corneal vertex was $-6.18 \pm$ 0.21 D, with a mean difference of 0.01 $\pm$ 0.06 D. The COR was better for the corneal back surface ($\pm$0.11 D) than for the front surface ($\pm$0.28 D); however, RR was better anteriorly (0.64%) than posteriorly (1.85%). This is depicted graphically in Figure 2. The 6 automated peripheral sagittal (axial) corneal curvature readings showed similar repeatability (COR $\pm$0.67 D; range 0.52 to 0.99 D; RR 1.19% to 2.30%) compared with the 2 central measurements, which were all less reliable

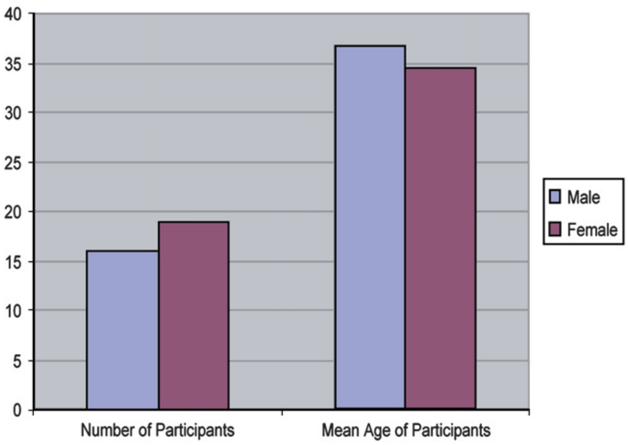

Figure 1. Patient demographics.

than the mean anterior K reading. The 6 peripheral tangential (meridional) corneal curvature readings were on average 50% less repeatable (COR ±1.02 D; range 0.76 to 1.25 D; RR 1.76% to 2.89%). The mean KPD was 1.22 ± 0.16 D, with a mean difference of 0.02 ± 0.10 D (COR ±0.20 D; RR 16.39%). Corneal curvature values are shown in Table 1.

Pupil

Pupil data are presented in Table 2.

Corneal Thickness

Corneal thickness and volume measurements are shown in Table 3. The mean CCT at the pupil center was 540.59 μm ± 36.88 and at the corneal vertex, 541.80 ± 37.12 μm. Both the COR (pupil center ±14.18 μm; corneal vertex ±14.06 μm) and RR (pupil center 2.62%; corneal vertex 2.59%) were comparable. On initial analysis, the peripheral corneal thickness measurements depicted on the Pentacam maps showed poor repeatability (mean COR ±26.28 μm, range 22.37 to 30.04 μm; mean RR 4.23%, range 3.66% to 4.64%). Repeat analysis using the corneal vertex as the reference point showed a marked improvement in the COR (mean ±16.00 μm; range 13.71 to 19.85 μm) and RR (mean 2.56%; range 2.24% to 3.07%). This improvement in repeatability is depicted by the line graph in Figure 3, in which pupil decentration is shown to have a definite impact on pachymetry readings.

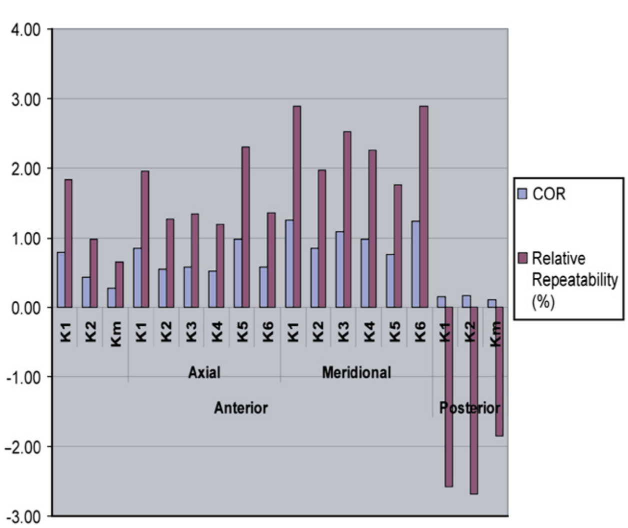

Figure 2. Repeatability of corneal curvature for simulated keratometry (K1, K2, Km) and at 4mm from the vertex (K1-K6): coefficient of repeatability (COR) and relative repeatability (%).

Anterior Chamber

Anterior chamber parameters, including COR and RR, are shown in Table 4.

Lens Densitometry

The data obtained for lens thickness and densitometry measurements were not included in the analysis as testing was conducted on undilated eyes, rendering the data unsuitable for these measurements. Moreover, Pentacam lens densitometry requires manual analysis and the focus of this study was on Pentacam's automated measurements. To our knowledge, no studies exist that look specifically at Pentacam measurements of lens densitometry, and this topic would lend itself to a comparison of other methods of quantifying cataract.

DISCUSSION

The automated measurements of corneal curvature and ACD recorded by Oculus Pentacam showed excellent repeatability, making this machine a clinically useful tool. Automated measurements of corneal thickness based on pupil center showed poor repeatability, but this improved when corneal thickness measurements were calculated manually using the corneal vertex as the reference point. All measurements did not show equal reproducibility, as graphically illustrated in Figure 4. Pupil diameter fared the worst, with an RR of 25.8%; KPD had a RR of 16.4%; anterior chamber angle, 14.4%; and anterior chamber volume, 5.7%. The other parameters all had an RR less than 5%.

Corneal Curvature

Corneal curvature measurements showed excellent repeatability (Figure 4), whether calculated centrally as simulated keratometry (on both back and front surfaces) or peripherally by the sagittal (axial) or tangential (meridional) method. Notably, the sagittal (axial) calculation method had a 50% lower COR than the

Table 1. Corneal curvature parameter mean values and reliabilities. For the anterior and posterior surfaces, K1 and K2 represent flat and steep keratometer-type values with Km being the mean of the two. K^1 to K^6 represent peripheral corneal curvature values taken clockwise from 12 o'clock at a 2.0 mm radius from the corneal vertex and are given for axial and meridional topography maps.

	Mean ± SD			
Parameter	Corneal Curvature (D)	Differences (D)	COR (D)	RR (%)
Anterior surface				
K1	42.66 ± 1.22	−0.03 ± 0.40	±0.78	1.83
K2	43.32 ± 1.40	−0.01 ± 0.21	±0.42	0.97
Km	42.98 ± 1.27	0.00 ± 0.14	±0.28	0.64
Axial				
K^1	43.19 ± 1.39	0.04 ± 0.43	±0.85	1.96
K^2	42.77 ± 1.27	−0.03 ± 0.28	±0.54	1.26
K^3	42.95 ± 1.25	−0.02 ± 0.29	±0.57	1.33
K^4	43.55 ± 1.40	−0.01 ± 0.26	±0.52	1.19
K^5	42.88 ± 1.29	−0.07 ± 0.50	±0.99	2.30
K^6	42.85 ± 1.28	0.00 ± 0.30	±0.58	1.35
Meridional				
K^1	43.27 ± 1.43	0.03 ± 0.64	±1.25	2.89
K^2	42.90 ± 1.39	0.00 ± 0.43	±0.84	1.96
K^3	42.99 ± 1.52	−0.04 ± 0.55	±1.08	2.52
K^4	43.15 ± 1.39	0.07 ± 0.50	±0.97	2.25
K^5	43.05 ± 1.42	0.03 ± 0.39	±0.76	1.76
K^6	42.82 ± 1.53	0.09 ± 0.63	±1.24	2.89
Posterior surface				
K1	−6.01 ± 0.22	0.00 ± 0.08	±0.16	−2.58
K2	−6.36 ± 0.26	0.00 ± 0.09	±0.17	−2.69
Km	−6.18 ± 0.21	0.01 ± 0.06	±0.11	−1.85
KPD	1.22 ± 0.16	0.02 ± 0.10	±0.20	16.39

COR = coefficient of repeatability; KPD = keratometric power deviation; RR = relative repeatability

tangential (meridional) curvature. This probably reflects the greater rate of change in peripheral corneal curvature that occurs with the tangential (meridional) method as a function of calculating curvature locally rather than with reference to the topographer axis.[20] This greater rate of change leaves the peripheral cornea vulnerable to variability arising from small changes in sampling position (Figure 5). Corneal front surface curvature (simulated keratometry) showed better relative repeatability than posterior corneal values, but the posterior cornea showed a better COR than the front corneal surface. The better COR posteriorly reflects the relative difference in magnitude of anterior and posterior corneal curvatures (which would not be seen if curvature was reported in millimeters); thus, RR is the more pertinent result. The reason for poorer RR for the posterior surface is not certain. It is possible that the Pentacam software has more difficulty finding and extracting the posterior corneal edge because the smaller difference in index of refraction between the cornea and aqueous gives rise to a lower contrast edge. The poorer RR posteriorly may also be a scale effect from reporting the results in diopters to 1 decimal place, which means there are 3 significant figures for anterior corneal curvature but only 2 significant figures for posterior corneal curvature. Perhaps reporting posterior corneal curvature to 2 decimal places would remove some of the measurement error that results from "rounding." For both the front and back surface curvatures, the mean K value showed better repeatability than K1 or K2, which is probably due to the noise-reducing benefit

Table 2. Pupil measurements, mean values, and reliabilities.

	Mean ± SD			
	Pupil Measurement	Differences	COR	RR (%)
Pupil diameter (mm)	3.04 ± 0.45	0.13 ± 0.40	±0.78	25.77
x axis (mm)	−0.01 ± 0.23	−0.01 ± 0.14	±0.27	−2991.83
y axis (mm)	−0.01 ± 0.12	0.00 ± 0.08	±0.15	−1771.24

COR = coefficient of repeatability; RR = relative repeatability

Table 3. Corneal thickness and volume parameter mean values and reliabilities. Peripheral thickness values are taken clockwise from 12 o'clock in a ring 3.0 mm from the corneal vertex.

Parameter	Corneal Thickness	Differences	COR	RR (%)
Pupil center (µm)				
Pupil center	540.59 ± 36.88	−1.11 ± 7.23	±14.18	2.62
Peripheral 1	647.50 ± 41.16	−0.74 ± 15.32	±30.04	4.64
Peripheral 2	611.70 ± 39.18	−0.79 ± 12.70	±24.88	4.07
Peripheral 3	611.43 ± 37.87	−2.13 ± 11.41	±22.37	3.66
Peripheral 4	611.87 ± 42.04	−0.29 ± 14.21	±27.84	4.55
Corneal vertex (µm)				
Corneal vertex	541.80 ± 37.12	−1.04 ± 7.17	±14.06	2.59
Peripheral 1	647.01± 41.73	11.64 ± 10.13	±19.85	3.07
Peripheral 2	615.71 ± 41.80	10.00 ± 7.20	±14.10	2.29
Peripheral 3	614.87 ± 38.47	9.01 ± 8.34	±16.35	2.66
Peripheral 4	612.11 ± 45.50	8.73 ± 7.00	±13.71	2.24
Corneal volume (mm^3)	58.88 ± 3.60	−0.06 ± 1.08	±2.11	3.58

COR = coefficient of repeatability; RR = relative repeatability

of averaging 2 values. Individual K1 and K2 values have comparable repeatability to peripheral sagittal (axial) curvature values K^1 through K^6. The precision demonstrated by Pentacam in measuring corneal curvature has potential positive implications for use of this measurement in intraocular lens (IOL) power calculations in normal eyes, for which precise measurement of corneal curvature helps decrease the postoperative refractive error. However, several existing Placido disk–based topographers exhibit superior anterior surface curvature repeatability.[21,22] The Pentacam does not meet the industry standard of repeatability, which is set to be ±0.25 D.[17]

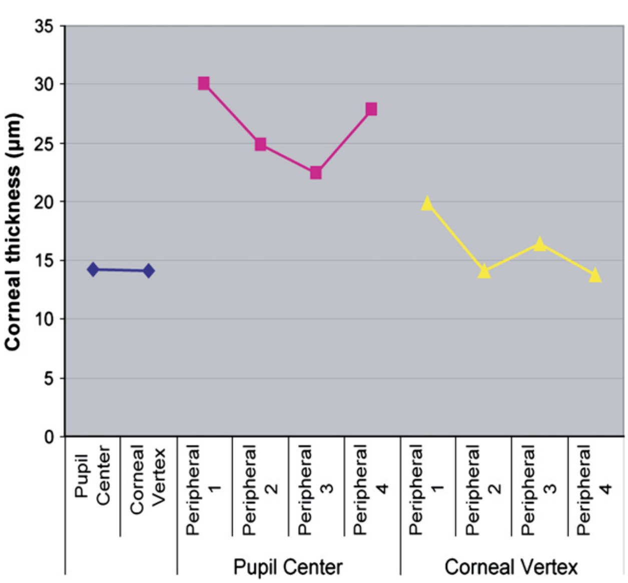

Figure 3. Coefficient of repeatability: pupil center versus corneal vertex.

According to the manufacturer, one advantage that contributes to the accuracy of Pentacam in measuring corneal curvature is that it does so centrally rather than paracentrally, as other imaging devices do. The Pentacam is able to measure the central cornea despite involuntary compensatory saccadic eye movements because it maintains a fixed point on the corneal vertex (J.T. Holladay, MD, et al. "Next-Generation Technology for the Cataract & Refractive Surgeon," Cataract & Refractive Surgery Today January 2005(suppl). Available at http://www.crstoday.com/PDF%20Articles/0105/PDFs/oculus.pdf. Accessed October 10, 2007). Holladay et al. predicted that the Pentacam would measure corneal curvature with an accuracy of ±0.50 D. Our findings show that repeatability of corneal curvature at individual points matched this prediction, but for mean K values, repeatability surpassed this (anterior ± 0.28D, posterior ±0.11 D). This is due to the averaging of measurements to determine the mean K, and similar gains in repeatability could be made by averaging curvature measurements at individual points over multiple measures.[14]

Keratometric Power Deviation

Keratometric power deviation showed results that are inconsistent with normal values reported in the manual. The Pentacam instruction manual gives less than 0.75 D as the normal value for KPD, with values more than 1.50 D indicating abnormal corneas from a disease process (eg, keratoconus) or intervention (photorefractive keratectomy, laser in situ keratomileusis, keratoplasty). Our mean KPD finding was 1.2 D; yet these values were acquired in a population established as normal. The manual clearly

Table 4. Anterior chamber parameters, mean values and reliabilities.

	Mean ± SD			
Parameter	Anterior Chamber	Differences	COR	RR (%)
Volume (mm^3)	191.92 ± 36.00	4.21 ± 5.56	±10.90	5.68
Depth (mm)	3.07 ± 0.32	0.01 ± 0.05	±0.09	3.07
Angle (degrees)	37.86 ± 6.75	0.08 ± 2.78	±5.45	14.41

COR = coefficient of repeatability; RR = relative repeatability

underestimates the KPD values in a normal population, and we recommend that these values be revised to normal = 1.22 D with an upper limit of 1.54 D, although, ideally, a larger study should be conducted to establish the KPD range that defines normal. The reliability of KPD scores was particularly poor. We again suggest that this is a result of rounding KPD to 1 decimal place. Because the mean value is close to 1, this means that KPD is reported in 1, or at most, 2 significant figures. Reporting KPD to 2 decimal places should improve its reliability markedly. The KPD is intended to demonstrate the influence of the posterior surface on corneal power by showing the difference between corneal power calculated from both surfaces (true net power) and corneal power calculated from anterior curvature values alone (using the keratometric refractive index). Such calculations rely on a series of assumptions that are not demonstrably appropriate; that is, that corneal curvature reported as diopters represents corneal power, that 2 surface curvatures can be combined in a thick lens formula to produce a meaningful result, and that simple subtraction of 2 "power" maps gives a meaningful difference score (KPD). The use of the term *corneal power* should not imply ray tracing was performed or refraction calculated.

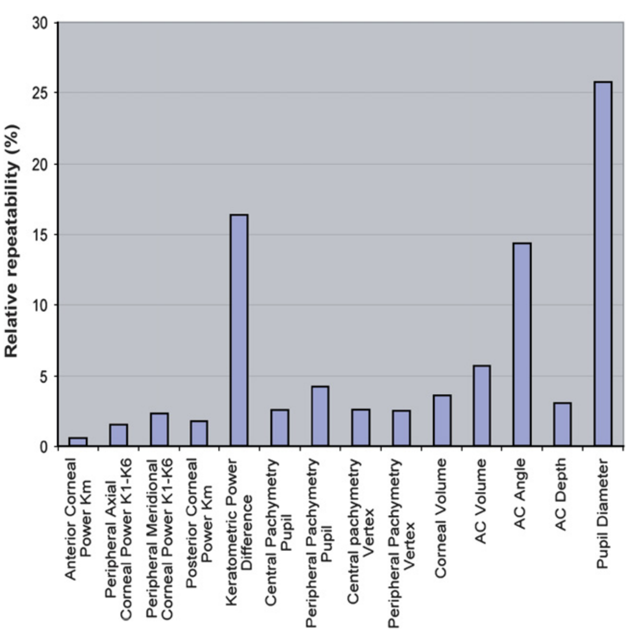

Figure 4. Summary of relative repeatability for all parameters.

Pupil Size and Decentration

Pupil size and decentration showed poor repeatability with decentration showing abnormal RR (x axis, 2991.8%, y axis, 1771.2%). Although the extreme numbers for pupil coordinates reflect that the mean value for x and y approaches zero, relative repeatability by definition will approach infinity. Regardless of this, the COR for pupil decentration was also very poor, with 0.27 mm and 0.15 mm representing unsatisfactory precision for centration. Testing was conducted under natural pupil conditions in undilated eyes. Pupil size is dynamic and affected by several factors (eg, light, accommodation, mechanical factors such as previous trauma) and is regulated by a complex set of neuronal factors and responses.[23] An attempt was made to standardize testing in that lighting was consistent, and the subject was asked to fixate on a black target in the middle of the blue scanning slit. Despite controlling these factors, pupillary unrest, or hippus, would be expected to occur over the 2-second cycle of the scan. Therefore, it is hardly surprising that these parameters showed poor repeatability. It is possible that pupil measurement would be more reliable if these dynamic effects were dampened by pharmacological pupil dilation, but we have not tested this.

That there can be an obvious change in pupil size and decentration between scans is evident in the example in Figure 6, which compares 2 scans taken 4 minutes and 34 seconds apart. Although the limitations imposed by pupil dynamism may mean that it is difficult to improve pupil measurement, we recommend that manufacturers consider ways to improve pupil measurement reliability. With the current lack of reliability, it would not be appropriate to use pupil measurement for any clinical purpose, such as suitability for refractive surgery or determining ablation zone size.

Corneal Thickness

Central corneal thickness showed good repeatability, although our initial findings were that peripheral pachymetry repeatability was poor. Repeat analysis of the topographical maps revealed that variability in pupil diameter and decentration affected peripheral pachymetry. An example of one of these maps showing the effect of pupil diameter and decentration is in

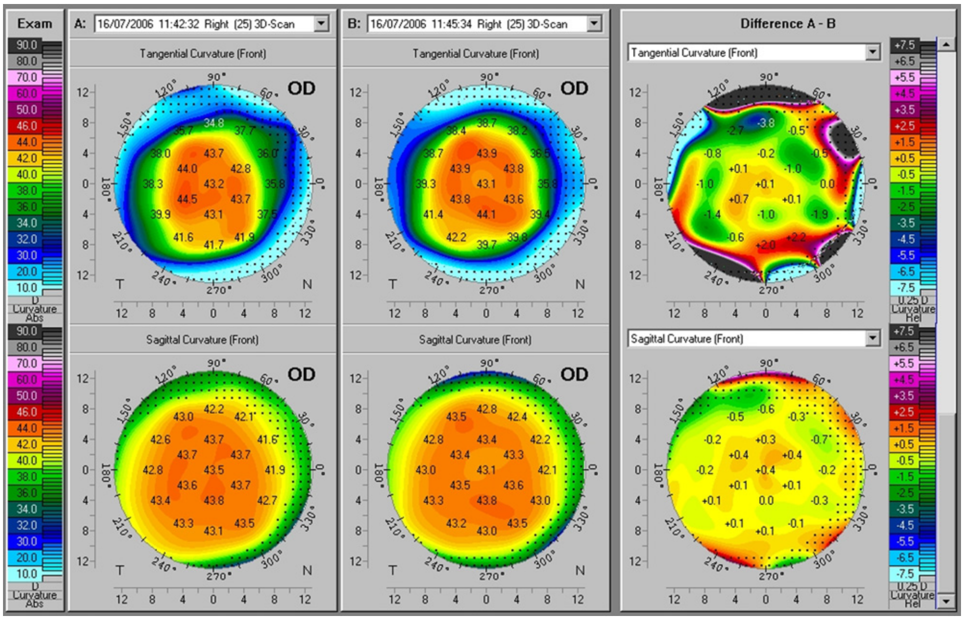

Figure 5. Test and retest curvature maps with a difference map calculated by both sagittal (axial) and tangential (meridional) methods for an individual. The curvature flattens out more rapidly with the tangential method, which leads to the poorer repeatability seen in the difference maps on both the 4.0 mm diameter ring and the 8.0 mm diameter ring.

Figure 6. The machine uses the pupil center as the reference point and calculates 4 peripheral corneal thickness measurements. We have demonstrated in this study that pupil center and decentration showed a great deal of variability between scans. This has a follow-on effect in that the sampling of peripheral corneal thickness occurs at points on the cornea that do not correspond, and it follows logically that corneal thickness shows poor repeatability. To overcome this problem, we used the corneal vertex as a reference point and manually rechecked all the maps and reacquired data for analysis. While this produced vastly better RR (mean COR $\pm$16.0 D, RR 2.6%, from COR $\pm$27.8 D and RR 4.2% using the pupil center as the reference point), the acquisition of the data was laborious and time consuming. We recommend that the automatic settings be altered to use the corneal vertex rather than the pupil center as the reference point for measuring corneal thickness. It can only be inferred that the logic underpinning the choice of pupil center as the reference is that traditional ultrasonic pachymetry is performed by placing the probe over the center of the pupil. However, due to the insufficient reliability of the Pentacam in defining pupil position, it is not feasible to adhere to this traditional approach.

Earlier studies have found CCT determined by Oculus Pentacam to be repeatable and on par with ultrasound pachymetry,[2,3,5] Orbscan (Bausch & Lomb), noncontact specular microscopy,[8] and the ACMaster (Zeiss).[9] Three studies found that Pentacam CCT values were closer to ultrasound pachymetry[2,3,6] and showed less variability than Orbscan, whereas

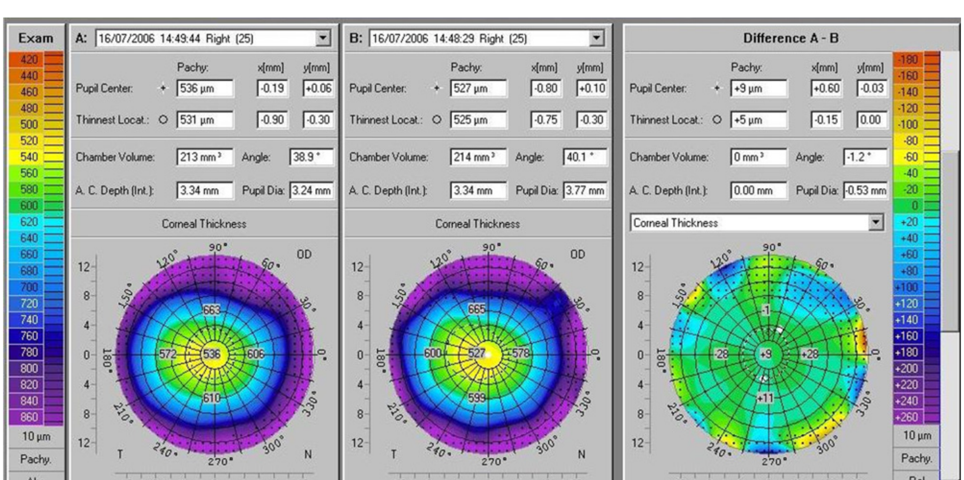

Figure 6. Effect of change in pupil diameter and decentration on peripheral pachymetry. Note the peculiar pupil shape in exam B, which probably results from a marked change in pupil size during the 2-second scan.

Buehl et al.[9] found CCT measurements correlated best between ACMaster and Pentacam. Lackner et al.[3] found that Pentacam showed the best interobserver repeatability of the 3 modalities. The findings of our study compare favorably with those in previous reliability studies measuring CCT (interobserver COR 14.06 μm and RR 2.6% at corneal vertex and COR ±14.1 μm and RR 2.6% at pupil center). Lackner et al.[3] found intraobserver COR ±13.5 μm; RR 2.5% and interobserver COR ±23.3 μm; RR 4.2%. O'Donnell and Maldonado-Codina[4] found similar repeatability (COR ±22.6 μm; RR 4.2%). Barkana et al.[2] also found good repeatability, with COR ±22.1 μm and the coefficient of interobserver reproducibility being 1.10%. Only Amano et al.[5] found better repeatability than the present study and the 3 previous studies (COR ±10.6 μm; RR 1.9%).

To our knowledge, only 2 other studies have tested the repeatability of peripheral pachymetry measurements using the Pentacam.[7,9] This is surprising given the importance of overall corneal thickness in planning and monitoring refractive surgery procedures.[24] Both Khoramnia et al.[7] and Buehl et al.[9] found that Pentacam measured CCT reliably, but peripheral corneal thickness values showed poorer repeatability, although retest limits of agreement were not reported in these studies; Buehl et al. concentrated on interchangeability with other devices. We recommend that the corneal vertex CCT be used for clinical purposes, for example in refractive surgery or glaucoma, as this is the most reliable corneal thickness measure.

Anterior Chamber

Examination of the anterior chamber is important in the assessment and management of glaucoma and in preoperative and postoperative assessment of IOL insertion, particularly anterior chamber phakic IOLs.[25,26] Rabsilber et al.[11] appeared to find better reliability in measuring anterior chamber parameters than our findings. We interpret their results as follows: anterior chamber volume COR ±3.23 mm^3, RR 2.0%; ACD COR ±0.04 mm, RR 1.3%; anterior chamber angle COR ±1.84, RR 5.3%, although the reporting of these results was unclear. The authors found an association with increasing age and reduced ACD and volume. Correspondingly, their findings (mean anterior chamber volume 160.3 ± 36.81 mm^3; mean ACD 2.93 ± 0.36 mm; mean anterior chamber angle 34.81 ± 5.05 degrees) in a normal population (mean age 46.6 ± 16.8 years) were slightly lower than our findings.[11] Two other papers[9,10] looked at the reliability of ACD measurements only. Lackner et al.[10] found comparable intraobserver and interobserver reliability in measuring ACD (intraobserver COR ±0.08 mm, RR 2.4%; interobserver COR ±0.07 mm, RR 2.3%). Our findings did not compare favorably with the previous studies: ACD showed the best repeatability (COR ±0.09 mm; RR 3.07%), and anterior chamber angle showed the worst repeatability (COR ±5.45 degrees, RR 14.4%). The reason for the differences between studies is uncertain. The most plausible explanation for ACD being the most constant of the 3 anterior chamber values is that it is unaffected by pupil changes. As we have shown, pupil measures are quite variable, which would affect anterior chamber volume and angle. These may also be affected by other factors such as accommodation and rate of aqueous production and drainage.[27] The reliability of anterior chamber volume and angle measures may also be affected by rounding error as anterior chamber volume is reported with no decimal places and anterior chamber angle is reported with 1 decimal place. The ACD is probably the most clinically useful parameter as it is used in planning IOL power calculation for cataract surgery[25,28] and phakic IOL placement[26,29] in refractive surgery. Therefore, the good reproducibility demonstrated in measuring ACD has positive implications for clinical utility.

CONCLUSION

Although many studies have evaluated the reliability of individual parameters measured by the Pentacam, this is to our knowledge the first study to test and objectively quantify the repeatability of automated Pentacam measurements comprehensively. The Pentacam showed good repeatability in imaging the anterior segment of the normal eye, and there is plenty of evidence to support this in the published literature. Underpinning this reliability is the machine's image acquisition specifications, which at the default level, often requires repeat measurement to achieve a reliable scan, thereby decreasing the "user friendliness of the machine." However, this compromise is requisite as more lenient image quality specifications would sacrifice reliability for a gain in clinical efficiency.

In summary, automated measurements showed a high degree of repeatability for corneal curvature, CCT, and ACD in normal eyes. This holds promise for the future utility of the Pentacam in planning and monitoring refractive surgery procedures, calculating IOL power, and managing glaucoma. Reproducibility of peripheral pachymetry readings was improved by manually acquiring data using the corneal vertex as the reference point. Dynamic parameters such as pupil size and decentration, as well as anterior chamber angle and volume, showed poorer repeatability.

Suggestions for potential improvements that could increase the clinical utility of the Pentacam are detailed in the discussion of this paper. As always, in defining the reliability and utility of new technology, further studies would be useful in validating the usefulness of the Pentacam as a clinical tool.

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