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A Comprehensive Evaluation of the Precision (Repeatability and Reproducibility) of the Oculus Pentacam HR

Colm McAlinden, Jyoti Khadka, and Konrad Pesudovs

Purpose. To evaluate the precision (repeatability and reproducibility) of the Pentacam HR (high-resolution) tomographer (Oculus, Wetzlar, Germany) across a large range of measurement parameters.

Methods. A randomly selected healthy eye of 100 subjects was scanned twice with the Pentacam HR by one observer for each of the three measurement modes: 25-picture (1 second) scan, 50-picture (2 second) scan, and cornea fine scan (50 pictures in 1 second). The repeatability of each scan mode was assessed. One additional 25-picture scan was acquired by a second observer to test reproducibility.

Results. Overall, the Pentacam HR had good precision, with the cornea fine scan returning the most precise results. The 25- and 50-picture scans showed similar precision. The repeatability limits, expressed as the within-subject SD $\times$ 1.96$\sqrt{2}$ of the anterior keratometry (*K*)1 and *K*2 readings with the standard 25-picture scan, were 0.25 and 0.36 D, respectively. Pachymetry maps, corneal maps, anterior chamber depth maps, corneal volume, topometric *Q* values and indices were also found to be precise. Poor precision was found for estimates of axis (astigmatic and progression index), pupil center pachymetry, single points on corneal maps, refractive power maps, and equivalent *K* readings.

Conclusions. Measurements taken with the Pentacam HR are repeatable and reproducible, especially those obtained with the cornea fine scan. Although the Pentacam HR is clearly a very useful clinical and research tool, the measurement of corneal axes, pupil center pachymetry, front meridional and axial maps, refractive power maps, and equivalent *K* readings should be interpreted with caution. (*Invest Ophthalmol Vis Sci.* 2011;52:7731–7737) DOI:10.1167/iovs.10-7093

The Oculus Pentacam is a non-invasive anterior segment tomographer utilizing a rotating Scheimpflug camera. It is capable of imaging the cornea, anterior chamber (AC), and lens, providing a plethora of measurements across the anterior segment. It received U.S. Food and Drug Administration approval in 2003 and has been used extensively in clinical practice and research settings.[1–3]

From the National Health and Medical Research Council (NH&MRC) Centre for Clinical Eye Research, Department of Optometry and Vision Science, Flinders Medical Centre and Flinders University of South Australia, Bedford Park, South Australia, Australia.

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Corresponding author: Colm McAlinden, Department of Optometry and Vision Science, Flinders Medical Centre and Flinders University of South Australia, Bedford Park, South Australia, 5042, Australia; colm.mcalinden@gmail.com.

The Pentacam HR tomographer was launched in 2005, with five times the image resolution of the basic, classic model. It has an improved optic design with a 1.45-megapixel camera. There is a range of additional features, such as the capability of a detailed cornea fine scan, a multirotation scan (50 pictures in 2 seconds), enhanced dynamic function (for accurate representation of phakic intraocular lenses [IOLs]), and improved fixation options.[4] The manufacturer's promotional material claims that the Pentacam HR has improved precision.

A comprehensive assessment of the reproducibility (change in observers) of the basic, classic model of the Pentacam has been reported.[5] This study found highly reproducible corneal curvature and AC parameters, but pupil measurements had poor reproducibility. Peripheral pachymetry readings were affected by pupil decentration and required manual analysis using the corneal apex as the point of reference to achieve good reproducibility. Recent studies with the new Pentacam HR have evaluated specific measurements such as corneal power and aberrations,[6,7] corneal thickness,[8–12] AC depth,[12,13] and lens densitometry.[14]

The purpose of this study was to comprehensively evaluate the Pentacam HR in terms of precision (repeatability and reproducibility) across a large range of its measurement parameters by repeated measures with two observers in a group of normal eyes.

Methods

In this prospective study, 100 subjects with normal healthy eyes were recruited. A randomly (fair coin toss) selected eye of each subject was scanned twice with the Pentacam HR by one observer on three different scan modes. The first mode was the standard 3D scan consisting of 25 pictures per second. The second mode was the 3D scan with 50 pictures in 2 seconds, and the third mode was the cornea fine scan with 50 pictures in 1 second. The time between repeated scans by observer 1 was the minimum possible—typically, 30 seconds. A second observer performed two scans on the same random eye with the standard 3D scan with 25 pictures per second. The time between the 25-picture (1 second) scan between observers 1 and 2 was the minimum possible—typically, 5 minutes. All scans were taken during a single sitting.

Inclusion and exclusion criteria were determined, to ensure that all the structures under measurement were free of eye disease and other problems likely to affect the ability to collect measurements. Inclusion criteria were any individual irrespective of age or ethnicity who had no known corneal disease or ocular pathology likely to affect fixation (e.g., age-related macular degeneration). Participants with cataract or refractive error were not excluded. Exclusion criteria were preexisting ocular surface pathology, history of eye trauma, contact lens wear, prior refractive surgery, use of eye drops, inability to fixate on the target, or any physical or mental impairment that precluded participation in the testing. The study was approved by Flinders Clinical Research Ethics Committee, and the research adhered to the tenets of the Declaration of Helsinki.

Testing was conducted with the patient's natural pupils under scotopic conditions. Participants remained positioned during all repeated measurements. They were instructed to keep both eyes open and look directly at the fixation target. Scans were taken in automatic release mode. Only scans that had an examination quality specification graded as "OK" were saved. During the change in observers, the patient was asked to sit back for a few moments.

The Pentacam HR

The Pentacam HR (Oculus; Optikgeräte GmbH, Wetzlar, Germany) is based on Scheimpflug slit image photography. It is a noninvasive anterior segment tomographer that uses a 475-nm monochromatic slit of light to illuminate the cornea and a 1.45-megapixel camera for photography. The camera rotates about the line of fixation during the scanning period. There are several scanning options available including a 25-picture (1 second) scan, a 50-picture (two second) scan, and a cornea fine (50 pictures in 1 second) scan. Using data from these pictures, the system calculates a 3D model of the anterior segment from up to 138,000 true elevation points. Any eye movement is detected by a second camera and corrected for in the process.

Measurements Acquired

Summary Data. For all scan modes, summary data are displayed that include standard keratometry (*K*) readings (*K*1 and *K*2) with associated axes, average *K* reading (*K*m), mean radius of curvature in the 7- to 9-mm area (*R*per), and minimum radius of curvature (*R*min) for both the anterior and posterior corneal surface. The refractive indices used for calculations involving the anterior and posterior corneal surfaces are 1.3375 and 1.376, respectively. Additional summary data include corneal volume, AC parameters, and pupil diameter.

Corneal Maps. The anterior and posterior corneal curvatures are measured from limbus to limbus in 360° and are reported in either millimeters or diopters. Meridional (tangential) and axial (sagittal) maps are produced for both the anterior and posterior cornea.[15] The Pentacam HR also produces maps termed elevation, true net power, keratometric power deviation (KPD), refractive power (anterior), and equivalent *K* reading (EKR) power.

Elevation maps provide an assessment of corneal height, above or below a reference surface. The reference surface can be altered to an ellipsoid, toric ellipsoid, or sphere. The reference surface used in this study was a sphere. The true net power is purported to be a measure of total corneal power, calculated using the thick lens formula and true refractive indices at each interface (air = 1.0, cornea = 1.376, and aqueous = 1.336).

$$\text{True Net Power} = \frac{1.376 - 1}{r_a} * 1000 + \frac{1.336 - 1.376}{r_p} * 1000 \quad (1)$$

where r_a is the anterior corneal radius and r_p is the posterior corneal radius.

This map assumes that corneal power is equal to the dioptric equivalent of the surface curvatures and that the anterior and posterior surfaces can be combined in the thick lens formula. This map is a dioptric curvature equivalent and should not imply that ray tracing was performed or refraction calculated. KPD is the difference between the anterior dioptric axial (sagittal) curvature and the true net power providing an assessment of the influence of the posterior corneal surface. KPD values up to 1.5 D are within normal limits, with greater values indicating abnormal steepening (e.g., keratoconus) or flattening (e.g., refractive surgery) of the cornea. Therefore, this is the difference between the traditional topography maps calculated using the standard keratometric refractive index of 1.3375 and the true net power map calculated with the true refractive indices. The refractive power map provides an evaluation of the optical effect of the anterior corneal surface and is displayed as the dioptric equivalent of the focal length. It is calculated using Snell's law and considers spherical aberration. The EKR map, in diopters, is calculated by the following formula[16]:

$$\text{EKR} = \frac{n_c}{r_a} + \frac{(n_k - 1)\text{RAT}_{bf}}{r_p}\left(1 - \frac{1}{\text{RAT}_{kc}}\right) \quad (2)$$

where n_c is the stromal refractive index of 1.3760; r_a is the anterior corneal radius; n_k is the standard keratometric index of 1.3375; RAT_{bf} is the normal ratio of back-to-front corneal radii of 0.822; r_p is the posterior corneal radius; and RAT_{kc} is the ratio of change in keratometric versus front surface power calculated as (1.3375 − 1.000)/(1.376 − 1.000) = 0.8976. With these calculations replacing the constants, the formula can be simplified to:

$$\text{EKR} = \frac{376}{r_a} - \frac{31.65}{r_p} \quad (3)$$

In the Holladay report, the EKR *K*1, *K*2, and *K*m are displayed in the 4.5-mm zone in the pupil center. However, values may also be displayed for zone diameters 1 to 7 mm.

Pachymetry Map. Corneal thickness values are available for the entire cornea. The map is centered on the corneal apex, but it also reports thickness values for the pupil center and thinnest point.

Anterior Chamber Map. The Pentacam HR calculates the AC volume, angle, and depth. The volume is calculated between the posterior cornea, iris, and lens over a 12-mm diameter centered on the corneal apex. The default angle displayed is the smallest angle in the Scheimpflug image; however, this may be calculated at other positions. The depth is calculated from the endothelium (default) along a line from the apex of the cornea to the iris or lens.

In all maps produced (cornea, pachymetry, and AC depth), we assessed the precision of measurements at 2 (P1), 3 (P2) and 4 (P3) mm inferiorly from the corneal apex along the vertical axis. These figures are displayed on each map and were not acquired manually with cursor clicks.

Corneal Volume. In the summary data, corneal volume is reported over a diameter of 10 mm, centered on the corneal apex, with the anterior and posterior cornea defining the boundaries for the calculation. It also calculates the volume at diameters of 3, 5, and 7 mm.

Asphericity. Corneal asphericity is frequently described by the *Q* value. A negative *Q* value indicates a prolate shape, whereas a positive value indicates an oblate shape. A range of other terms are used to describe asphericity or corneal shape, such as eccentricity, shape factor, and *P* value.[17] Although all these indices are reported by the Pentacam HR, they are all methods of reporting the same information, and so precision of one measure implies precision of others; therefore, the *Q* value was assessed in this study. The mean *Q* value is reported at 20° to 40° in 5° steps.

Indices. The Pentacam HR calculates a range of indices from anterior curvature and elevation data. It produces the index of surface variance (ISV), index of vertical asymmetry (IVA), keratoconus index (KI), center keratoconus index (CKI), index of height asymmetry (IHA), index of height decentration (IHD), and topographic keratoconus classification (TKC).

Pachymetric Graphs. Two pachymetric graphs are produced: the corneal thickness spatial profile (CTSP) and the percentage of increase of thickness (PIT). The CTSP is a graph of the distance to the thinnest point on the cornea (*x*-axis) against the absolute corneal thickness (*y*-axis). The PIT graph uses the same *x*-axis, but the *y*-axis displays the increase in thickness related to the thinnest point, calculated as:

$$\text{PIT} = \frac{(\text{mean corneal thickness on the ring}) - (\text{thinnest corneal thickness})}{\text{thinnest corneal thickness}} \quad (4)$$

A table is produced providing the mean values for both graphs from 0 to 8 mm in 2-mm increments. A progression index (maximum and minimum) is also displayed, with its associated axial position. The axial position indicates the alignment of the meridians with the smallest or largest change in corneal thickness.

Statistical Analysis

The precision of the Pentacam HR in terms of repeatability and reproducibility was assessed as per the recommendations from the British Standards Institute and the International Organization for Standardization.[18] Precision arises due to the variability found with repeated measurements on presumably identical subjects. Repeatability refers to the variability in repeated measurements when the observer, instrument, calibration, environment, and time interval between measurements are kept constant. Reproducibility refers to variability when one or more of these factors are varied. In this study, reproducibility was assessed by a change in observer. The time interval was the minimum time possible.

Repeatability (S_r) equals the within-subject SD for repeated measures with the same observer, which is derived by a one-way analysis of variance (ANOVA). The repeatability limit (r) is reported as $1.96\sqrt{2} \times S_r$ which gives the likely limits within which 95% of measurements should occur. S_r and r were calculated for the repeated measurements with the three scan modes for observer 1. The reproducibility (S_R) and reproducibility (R) limits were calculated in the same way, using a one-way ANOVA from the first measurement results from observer 1 compared with the measurement results from observer 2 for the 25-picture scan mode. Data were directly exported from the Pentacam HR to spreadsheets by customized software. However, export was not possible for the following maps: meridional/tangential, axial/sagittal, elevation, keratometric power, refractive power, relative pachymetry, and EKR power. It was also not possible to export the Holladay report and topometric mean *Q* values. These data were manually entered into spreadsheets. Data were screened for typographical errors, and double-entry techniques were used when necessary (SPSS, ver. 19; IBM-SPSS Corp., Somers, NY).

Results

One hundred random eyes (53 left) of 100 subjects (69 female; mean age, 33.7 years; age range, 19–68) were successfully scanned by both observers. The mean corneal astigmatism ($K1-K2$) for all patients using the 25-picture scan with the first observer was −0.82 D (standard deviation = 0.57 D; range, 0 to −2.60 D). Repeatability and reproducibility, with their associated limits, are shown in Table 1. Overall, the Pentacam HR had good precision, with the cornea fine scan providing the most precise results. The 25-picture (1 second) and 50-picture (2 seconds) scans provided similar precision.

Repeatability

Summary Data. Standard corneal *K*1 and *K*2 measurements were in general found to be very repeatable with all three scan modes. The cornea fine scan provided the most repeatable measurements with comparable repeatability with the 25- and 50-picture scans. The worst repeatability limit was for the anterior *K*2 reading, with a value of 0.39 D with the 50-picture scan. Axis values were found to demonstrate poor repeatability limits for all scan modes (r up to 125°). Summary data in terms of KPD, AC depth, and pupil diameter were very repeatable for all scan modes. AC volume measures were less repeatable for the 25-picture scan ($r = 16.87$ mm^3) compared with those for the 50-picture scan ($r = 9.42$ mm^3). AC angle estimates were most repeatable for the 50-picture scan ($r = 4.60°$), with similar repeatability for the 25-picture scan ($r = 6.12°$) and the cornea fine scan ($r = 7.84°$).

Corneal Maps. Front surface meridional and axial maps had poor repeatability with all three measurement modes. Back surface estimates were found to provide better repeatability. The 50-picture scan and cornea fine scan were the most repeatable for meridional and axial maps. Front surface elevation maps were generally more repeatable than back surface elevation maps. For front and back surface elevation, the cornea fine scan proved to be the best and the 25-picture scan the worst. In general the more peripheral positions had poorer repeatability. The true net power, keratometric power, and relative pachymetry maps were very repeatable for all scan modes. The refractive power (front) maps and equivalent *K*-reading maps demonstrated poor repeatability for all three measurement modes. The Holladay report equivalent *K*1, *K*2, and *K*m estimates also displayed poor repeatability.

Pachymetry Map. Pachymetry measurements with respect to the pupil center were not possible with the cornea fine scan mode. Both the 25- and 50-picture scan provided poor repeatability limits for pupil center measures with values of 111.63 and 756.54 μm, respectively. At the corneal apex, the cornea fine scan was the most repeatable and the 50-picture scan was the least. Peripheral corneal thickness measurements were most repeatable with the cornea fine scan and similar repeatability was found with the 25- and 50-picture scans.

Anterior Chamber Map. The AC depth map was not possible with the cornea fine scan. The 25- and 50-picture scans were very repeatable in all three positions.

Corneal Volume. Corneal volume measurements at all diameters were very repeatable with all scan modes. The cornea fine scan provided the most repeatable measurements and the 25-picture scan the least.

Asphericity and Indices. The topometric mean *Q* value was very repeatable and similar across all scan modes ($r <$ 0.37). Indices IVA, KI, CKI, and IHD were in general very repeatable across all scan modes. ISV and IHA were less repeatable in all three measurement modes.

Pachymetric Graphs. Pachymetric graphs were very repeatable for the cornea fine scan and least for the 50-picture scan (r up to ~25 μm). The 10-mm diameter displayed less repeatable results compared with smaller diameters. The progression index was generally very repeatable for all scan modes, but the axis displayed poor repeatability.

Reproducibility

The reproducibility of the 25-picture scan between the two observers was found to be generally good. In comparison to repeatability, reproducibility was marginally worse for most of the measurements.

Discussion

Automated measurements with the Pentacam HR provided good repeatability and reproducibility across the spectrum of measurements, indicating the usefulness of the system in clinical and research settings. Notably, there were some differences in precision across measurement modes. The cornea fine scan provided the most repeatable results, illustrating the benefit of additional data over a short duration. The 25- and 50-picture scan provided similar precision, with the 25-picture scan being marginally better overall. However, for some measurements, the 50-picture scan provided the most repeatable results, such as AC angle, AC volume, and pupil size. This indicates that the gain in additional

Table 1. Precision (Repeatability and Reproducibility with Corresponding Limits) of the Pentacam HR for the Three Measurement Modes

Measurement	Repeatability, S_r (Repeatability Limit, r)			Reproducibility S_R (Reproducibility limit, R) (25 Pictures, 1 Second)
	25 Pictures (1 Second)	50 Pictures (2 Seconds)	Cornea Fine (50 Pictures, 1 Second)	
Anterior				
*K*1, D	0.09 (0.25)	0.08 (0.22)	0.07 (0.19)*	0.10 (0.28)
*K*2, D	0.13 (0.36)	0.14 (0.39)	0.09 (0.25)*	0.13 (0.36)
*K*m, D	0.12 (0.33)*	0.21 (0.58)	0.18 (0.50)	0.27 (0.75)
Axis, deg	34.23 (94.82)*	45.32 (125.54)	34.96 (96.84)	40.06 (110.97)
Q-value, 30 deg	0.03 (0.08)	0.01 (0.03)*	0.04 (0.11)	0.03 (0.08)
Rper, mm	0.01 (0.03)*	0.01 (0.03)*	0.03 (0.08)	0.01 (0.03)
Rmin, mm	0.05 (0.14)	0.04 (0.11)	0.03 (0.08)*	0.04 (0.11)
Posterior				
*K*1, D	0.03 (0.08)*	0.04 (0.11)	0.04 (0.11)	0.03 (0.08)
*K*2, D	0.04 (0.11)	0.04 (0.11)	0.04 (0.11)	0.04 (0.11)
*K*m, D	0.03 (0.08)	0.03 (0.08)	0.03 (0.08)	0.03 (0.08)
Axis, deg	46.56 (126.20)	46.26 (128.14)*	48.75 (135.04)	45.06 (124.82)
Rper, mm	0.03 (0.08)	0.03 (0.08)	0.03 (0.08)	0.03 (0.08)
Rmin, mm	0.03 (0.08)*	0.04 (0.11)	0.04 (0.11)	0.03 (0.08)
Summary data				
K-max front, D	0.29 (0.80)	0.27 (0.75)	0.20 (0.55)*	0.28 (0.78)
X-axis, mm	0.36 (1.00)	0.37 (1.02)	0.25 (0.69)*	0.35 (0.97)
Y-axis, mm	1.01 (2.80)	0.69 (1.91)*	0.96 (2.66)	1.07 (2.96)
Corneal volume, mm^3	0.51 (1.41)	0.54 (1.50)	0.48 (1.33)*	0.59 (1.63)
KPD, D	0.06 (0.17)*	0.06 (0.17)*	0.09 (0.25)	0.07 (0.19)
AC volume, mm^3	6.09 (16.87)	3.40 (9.42)*	—	8.93 (24.74)
AC angle, degrees	2.21 (6.12)	1.66 (4.60)*	2.83 (7.84)	2.69 (7.45)
AC depth, mm	0.01 (0.03)*	0.01 (0.03)*	0.09 (0.25)	0.03 (0.08)
Pupil diameter, mm	0.20 (0.55)	0.12 (0.33)*	—	0.32 (0.89)
Meridional/tangential				
Front, D				
P1	1.76 (4.88)	1.74 (4.82)*	1.79 (4.96)	1.77 (4.90)
P2	1.95 (5.40)*	1.98 (5.48)	2.11 (5.84)	2.25 (6.23)
P3	3.77 (10.44)	3.29 (9.11)*	3.75 (10.39)	3.03 (8.39)
Back, D				
P1	0.35 (0.97)	0.35 (0.97)	0.32 (0.89)*	0.34 (0.94)
P2	0.39 (1.08)*	0.39 (1.08)*	0.40 (1.11)	0.38 (1.05)
P3	0.98 (2.71)	0.72 (1.99)	0.71 (1.97)*	0.80 (2.22)
Axial/sagittal				
Front, D				
P1	1.46 (4.04)	1.45 (4.02)*	1.45 (4.02)*	1.46 (4.04)
P2	1.49 (4.13)	1.47 (4.07)*	1.48 (4.10)	1.49 (4.13)
P3	1.47 (4.07)	1.44 (3.99)*	1.52 (4.21)	1.50 (4.16)
Back, D				
P1	0.23 (0.64)*	0.75 (2.08)	0.23 (0.64)*	0.23 (0.64)
P2	0.26 (0.72)	0.26 (0.72)	0.25 (0.69)*	0.26 (0.72)
P3	0.26 (0.72)	0.24 (0.66)*	0.26 (0.72)	0.25 (0.69)
Elevation				
Front, μm				
P1	3.24 (8.97)	3.30 (9.141)	3.17 (8.78)*	3.26 (9.03)
P2	4.92 (13.63)*	5.00 (13.85)	4.93 (13.66)	5.08 (14.07)
P3	8.70 (24.10)	8.86 (24.54)	8.23 (22.80)*	9.25 (25.62)
Back, μm				
P1	6.28 (17.40)	6.23 (17.26)	5.90 (16.34)*	6.16 (17.06)
P2	7.63 (21.14)	7.99 (22.13)	7.41 (20.53)*	8.46 (23.43)
P3	14.96 (41.44)*	15.63 (43.30)	15.00 (41.55)	16.20 (44.87)
True net power, D				
P1	0.13 (0.36)*	0.16 (0.44)	0.13 (0.36)*	0.18 (0.50)
P2	0.19 (0.53)	0.20 (0.55)	0.18 (0.50)*	0.20 (0.55)
P3	0.26 (0.72)*	0.28 (0.78)	0.36 (1.00)	0.30 (0.83)
Keratometric power, D				
P1	0.14 (0.39)	0.14 (0.39)	0.13 (0.36)*	0.13 (0.36)
P2	0.15 (0.42)	0.15 (0.42)	0.14 (0.39)*	0.15 (0.42)
P3	0.16 (0.44)	0.15 (0.42)*	0.17 (0.47)	0.16 (0.44)
Refractive power, front, D				
P1	1.55 (4.29)	1.54 (4.27)*	1.54 (4.27)*	1.56 (4.32)
P2	1.69 (4.68)	1.68 (4.65)*	1.69 (4.68)	1.70 (4.71)
P3	1.87 (5.18)	1.83 (5.07)*	1.94 (5.37)	1.90 (5.26)
Relative pachymetry, %				
P1	1.97 (5.46)*	2.04 (5.65)	1.97 (5.46)*	2.01 (5.57)
P2	1.35 (3.74)	1.35 (3.74)	1.34 (3.71)*	1.29 (3.57)
P3	2.39 (6.62)	2.26 (6.26)	2.20 (6.09)*	2.35 (6.51)
Equivalent *K*-reading power, D				
P1	1.56 (4.32)	1.54 (1.50)*	1.55 (4.29)	1.56 (4.32)
P2	1.70 (4.71)	1.69 (4.68)*	1.71 (4.74)	1.72 (4.76)
P3	1.93 (4.35)	1.91 (5.29)*	2.01 (5.57)	1.95 (5.40)

(*continues*)

Table 1 (*continued*). Precision (Repeatability and Reproducibility with Corresponding Limits) of the Pentacam HR for the Three Measurement Modes

Measurement	Repeatability, S_r (Repeatability Limit, r) 25 Pictures (1 Second)	50 Pictures (2 Seconds)	Cornea Fine (50 Pictures, 1 Second)	Reproducibility S_R (Reproducibility limit, R) (25 Pictures, 1 Second)
Holladay report equivalent *K*-reading				
*K*1, D	1.33 (3.68)*	1.33 (3.68)*	1.35 (3.74)	1.33 (3.68)
*K*2, D	1.43 (3.96)*	1.45 (4.02)	1.45 (4.02)	1.42 (3.93)
*K*m, D	1.35 (3.74)*	1.35 (3.74)*	1.36 (3.77)	1.34 (3.71)
Q-value 4.5 mm. deg	0.19 (0.53)	0.18 (0.50)	0.16 (0.44)*	0.19 (0.53)
Radii ratio, %	1.39 (3.85)	1.41 (3.91)	1.33 (3.68)*	1.37 (3.79)
Estimated pre-ref, D				
*K*m	1.65 (4.57)	1.65 (4.57)	1.62 (4.49)*	1.62 (4.49)
Ref change	0.76 (2.11)	0.76 (2.11)	0.71 (1.97)*	0.73 (2.02)
Pachymetry				
Pupil center (μm)	40.30 (111.63)*	273.12 (756.54)	—	55.00 (152.35)
X-axis (mm)	4.02 (11.14)*	4.34 (12.02)	—	5.24 14.51)
Y-axis (mm)	4.72 (13.07)*	4.91 (13.60)	—	5.91 (16.37)
Apex (μm)	3.74 (10.36)	4.32 (11.97)	3.15 (8.73)*	4.36 (12.08)
Thinnest (μm)	3.25 (9.00)	4.11 (11.39)	3.21 (8.89)*	4.58 (12.69)
Pachymetry map, μm				
P1	4.60 (12.74)	4.46 (13.35)	3.52 (9.75)*	5.55 (15.37)
P2	6.30 (17.45)	6.25 (17.31)	5.21 (14.43)*	6.32 (17.51)
P3	8.69 (24.07)	8.24 (22.82)	7.86 (21.77)*	8.59 (23.79)
AC depth map, mm				
P1	0.48 (1.33)	0.46 (1.27)*	—	0.46 (1.27)
P2	0.42 (1.16)	0.41 (1.14)*	—	0.41 (1.14)
P3	0.42 (1.16)*	0.43 (1.19)	—	0.43 (1.19)
Corneal volume, mm^3				
3 mm diameter	0.10 (0.28)	0.04 (0.11)	0.03 (0.08)*	0.03 (0.08)
5 mm diameter	0.28 (0.78)	0.09 (0.25)	0.07 (0.19)*	0.09 (0.25)
7 mm diameter	0.18 (0.50)	0.62 (1.72)	0.15 (0.42)*	0.21 (0.58)
Topometric mean Q-value, deg				
20	0.12 (0.33)	0.12 (0.33)	0.12 (0.33)	0.13 (0.36)
25	0.11 (0.30)*	0.11 (0.30)*	0.12 (0.33)	0.12 (0.33)
30	0.12 (0.33)	0.11 (0.30)*	0.12 (0.33)	0.12 (0.33)
35	0.12 (0.33)	0.12 (0.33)	0.12 (0.33)	0.12 (0.33)
40	0.12 (0.33)*	0.13 (0.36)	0.13 (0.36)	0.14 (0.39)
Indices				
ISV	1.07 (2.96)	1.25 (3.46)	0.67 (1.86)*	1.19 (3.30)
IVA	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)
*K*I	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)
CKI	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)
IHA	1.34 (3.71)	1.65 (4.57)	1.26 (3.49)*	1.49 (4.13)
IHD	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)	0.01 (0.03)
Pachymetric graphs				
0 mm CTSP/μm	3.62 (10.03)	4.00 (11.08)	2.88 (7.98)*	4.41 (12.22)
PTI/%	—	—	—	—
2 mm CTSP/μm	3.63 (10.06)	4.03 (11.16)	2.94 (8.14)*	4.36 (12.08)
PTI/%	0.33 (0.91)	0.28 (0.78)	0.26 (0.72)*	0.25 (0.69)
4 mm CTSP/μm	4.02 (11.14)	4.36 (12.08)	3.20 (8.86)*	4.68 (12.96)
PTI/%	0.37 (1.02)	0.37 (1.02)	0.26 (0.72)*	0.38 (1.05)
6 mm CTSP/μm	4.73 (13.10)	4.92 (13.63)	3.88 (10.75)*	5.44 (15.07)
PTI/%	0.41 (1.14)	0.42 (1.16)	0.37 (1.02)*	0.39 (1.08)
8 mm CTSP/μm	6.06 (16.79)	6.49 (17.98)	5.00 (13.85)*	6.71 (18.59)
PTI/%	0.62 (1.71)	0.64 (1.77)	0.55 (1.52)*	0.64 (1.77)
10 mm CTSP/μm	7.39 (20.47)*	8.87 (24.57)	8.14 (22.55)	9.42 (26.09)
PTI/%	3.73 (10.33)	1.07 (2.96)*	1.17 (3.24)	5.18 (14.35)
Progression index				
Min	0.05 (0.14)	0.06 (0.17)	0.04 (0.11)*	0.06 (0.17)
Axis	91.81 (254.31)	99.14 (274.62)	89.18 (247.03)*	93.50 (259.00)
Max	0.10 (0.28)	0.08 (0.22)*	0.08 (0.22)*	0.08 (0.22)
Axis	67.35 (186.56)	70.95 (196.53)	62.24 (172.40)*	76.12 (210.85)

*K*1, *K*2: keratometry readings 1,2; *K*m: mean keratometry reading; Rper: mean radius of curvature in the 7–9-mm area of the cornea; Rmin: minimum radius of curvature; P1, 2, 3: peripheral measurement at 2, 3, and 4 mm inferiorly from apex, respectively; KPD: keratometric power deviation; AC: anterior chamber; ISV: index of surface variance; IVA: index of vertical asymmetry; *K*I: keratoconus index; CKI: center keratoconus index; IHA: index of height asymmetry; IHD: index of height decentration; CTSP: corneal thickness spatial profile; PTI: percentage of increase of thickness; N/A: not applicable.

* Most repeatable measurement from the three measurement modes.

information from multiple scans is offset by loss due to the extra time taken: The image acquisition time for the 50-picture scan is twice as long as that for the 25-picture scan. The decline in precision with the longer scan is probably due to the risk of greater eye movement and pupil hippus and the need for greater patient compliance.

Reproducibility was assessed by using a second observer, and results indicate excellent reproducibility across most of the measurements made. Reproducibility and repeatability for most measurements were comparable in clinical interpretability. One would expect these to be similar, given that scans were acquired on automatic release mode which requires minimal user input. It is interesting to note that, on the whole, reproducibility was worse than repeatability, indicating that there were some, albeit small, user-related effects. Such user-related effects may be in the form of the how quickly the user moved the device into the correct position for automatic capture, with a shorter time resulting in better subject cooperation and concentration, instructions and encouragement to the subject, and steadiness of device and associated apparatus during capture.

Some measures showed poor precision: axes (astigmatic and progression index), pupil center pachymetry, front meridional and axial maps, refractive power maps, and EKRs. For example, the repeatability limit of the anterior corneal astigmatic axis with the cornea fine scan was 96.84°. This axis value is reported as the location of the steepest $K2$ reading. Of course, in a relatively spherical cornea, small cylinders may be detected at markedly different positions, although if represented in vector terms these would represent small differences. Therefore, there may be no problem with corneal astigmatism findings, although users are advised to interpret axes of small cylinders with caution. The precision of the pupil center pachymetry measurements were poor, with a repeatability limit of 111.63 μm for the 25-picture scan and 756.54 μm for the 50-picture scan. The main reason for this is that patients were examined with natural pupils, and so pupillary hippus came into play, and it is likely that the position of the pupil center changed between measurements.[19] The poor precision found with front meridional and axial maps may be secondary to small eye movements, where the repeated measure may not be an exact corresponding point on the anterior corneal surface. Back surface estimates demonstrated better precision. The poor precision found with the equivalent $K1$, $K2$, and Km readings in the Holladay report may be secondary to the fact that their calculation is centered on a 4.5-mm zone around the pupil center. Because of the dynamic nature of the pupil with a change in the pupil center position, repeated K readings may be noncorresponding and hence may display poor precision estimates.

Other research groups have looked at the precision of some of the Pentacam HR output. Read et al.[6] found good repeatability for axial power and corneal aberrations with the 50-picture scan. Results were compared to videokeratoscopy with the E300 corneal topographer (Medmont International Pty., Ltd., Vermont, VIC, Australia) in terms of repeatability and agreement. The repeatability of the Medmont E300 was found to be marginally better, and reasonable agreement was found between the two devices; however, for certain aberrations, there was poor agreement. Piñero et al.[7] investigated the precision of the Pentacam HR for measuring curvature and aberrations of the posterior cornea in 20 eyes. The study used the cornea fine scan mode and found the repeatability of the posterior $K1$ and $K2$ to be 0.03 and 0.04 D, respectively. This result is in agreement with the repeatability of the cornea fine scan in the present study, which was 0.04 D (r = 0.11 D) for both $K1$ and $K2$. The present study also showed good precision for anterior $K1$ and $K2$ readings with all three measurement modes, with the cornea fine scan providing the most precise estimates (Fig. 1).

Several studies have assessed central corneal thickness (CTT) measurements with the Pentacam HR.[8–12] Chen et al.[8] found good precision with the 25-picture scan; however, they found better precision with optical coherence tomography (OCT). They also compared both Pentacam HR and OCT measures to ultrasound pachymetry (UP), concluding that the Pentacam HR and OCT can be used interchangeably and that both devices are comparable with UP.[8] de Sanctis et al.[9] compared the precision and agreement of CTT measurements between the Pentacam HR and UP in a group of 33 keratoconic eyes, finding the Pentacam HR to be more precise. Jahadi Hosseini et al.[10] found good correlation and agreement between the Pentacam HR; Galilei (Ziemer, Port, Switzerland), also based on Scheimpflug imaging; and UP for the thinnest and CTT in 47 eyes. Arbelaez et al.[11] also reported good correlation between UP and the Pentacam HR. Doors et al.[12] found the repeatability of CCT at the pupil center (25-picture scan) in 66 healthy eyes to be 4.0 μm, whereas in the present study, it was found it to be much worse at 40.30 μm (r = 111.63).

Salouti et al.[13] compared the AC depth agreement between the Pentacam HR (50-picture scan), Galilei, and Orbscan II (Bausch & Lomb, Rochester, NY). Their findings indicated that the Orbscan II gave consistently higher measurements for AC depth than did the Galilei and Pentacam HR. However, the Galilei and Pentacam HR were within clinically acceptable levels and may be used interchangeably in the measurement of AC depth. Kirkwood et al.[14] assessed the precision of the Pentacam HR for measuring lens densitometry in eyes with and

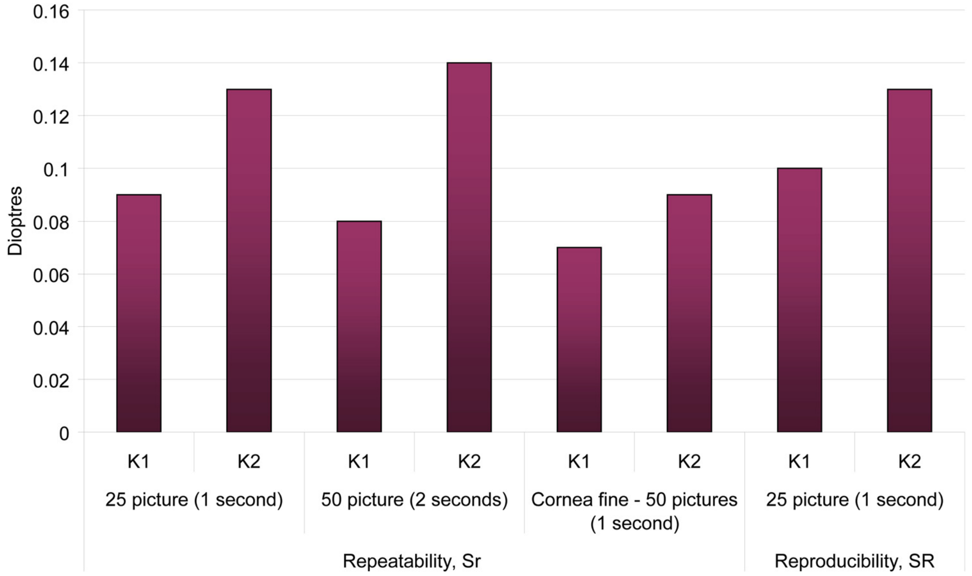

FIGURE 1. Repeatability (S_r) and reproducibility (S_R) of anterior $K1$ and $K2$ readings for the three measurement modes of the Pentacam HR.

without cataract, using the 25-picture scan. Both the repeatability and reproducibility (a change in observer) were high for all densitometry metrics evaluated, although the cataract group displayed marginally less repeatability than did the noncataract group.

The good, repeatable results with the Pentacam HR in the present study may be due to improvements over the basic, classic model. The HR model is capable of capturing more than five times the number of data points than the original model. When compared to a previous comprehensive study of the reproducibility of the basic, classic Pentacam, this study showed improved precision in the measurement of CCT and AC depth.[5] This finding may suggest that the improved resolution of the HR version has helped with the determination of the posterior corneal surface. Such improvements are welcomed with noncontact devices becoming an attractive alternative as they eliminate the disadvantages of contact methods, such as the risk of corneal abrasion, infection, and discomfort.

In conclusion, the Pentacam HR was found to be precise in terms of repeatability and reproducibility across the range of measurements assessed. Exceptions to this were axis estimates, pupil center pachymetry, front meridional and axial maps, refractive power maps, and EKRs. The cornea fine scan mode was the most precise of the three measurement modes. The 2-second 50-picture scan provided no major advantage for its use over the 1-second 25-picture scan. Table 1 can be used as a reference for the precision estimates in this study and the accepted precision for 95% of measurements.

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