

Central corneal thickness measurement with the Pentacam Scheimpflug system, optical low-coherence reflectometry pachymeter, and ultrasound pachymetry

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PURPOSE: To assess the intraoperator repeatability and interoperator reproducibility of central corneal thickness measurements by the Pentacam Scheimpflug imaging system (Oculus) and the optical low-coherence reflectometer (OLCR) pachymeter (Haag-Streit) and to compare them with those of ultrasound (US) pachymetry.

SETTING: Assaf Harofe Medical Center Ophthalmology Outpatient Clinic, Zerifin, Israel.

METHODS: Repeatability was determined from 10 successive measurements in each of 4 healthy patients. Reproducibility for the Pentacam Scheimpflug system was determined from measurements by 2 operators in each of 24 patients; in these 24 patients, central corneal thickness measurements were compared between the Pentacam and US pachymetry. For the OLCR pachymeter, reproducibility was determined from measurements by 2 operators in each of 16 patients, in whom central corneal thickness was also measured with the Pentacam.

RESULTS: Mean coefficient of repeatability was 0.84% for the Pentacam Scheimpflug system and 0.33% for the OLCR pachymeter. For the Pentacam, the coefficient of interoperator reproducibility was 1.10% and the 95% limits of agreement were $-10.2 \mu\text{m}$ to $+11.9 \mu\text{m}$. Mean difference between Pentacam and US was $6.09 \mu\text{m}$. For the OLCR pachymeter, the coefficient of interoperator reproducibility was 0.59% and the 95% limits of agreement were $-5.4 \mu\text{m}$ to $+7.0 \mu\text{m}$. Mean difference between central corneal thickness values obtained with the OLCR pachymeter and Pentacam Scheimpflug system was $1.7 \mu\text{m}$.

CONCLUSIONS: Objective, noncontact measurement of central corneal thickness with the Pentacam Scheimpflug system and OLCR pachymeter was convenient and yielded excellent intraoperator repeatability and interoperator reproducibility. Central corneal thickness values obtained with the Pentacam were similar to those obtained with both the OLCR pachymeter and an US pachymeter. Further research is needed to corroborate whether central corneal thickness measurements by the Pentacam and OLCR devices can be used interchangeably and are more clinically useful than US pachymetry.

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The measurement of central corneal thickness has become increasingly important in ophthalmic practice. For example, refractive surgery is routinely planned according to preoperative measurement of central corneal thickness,^{1,2} and accurate determination of intraocular pressure may need to be modified according to central corneal thickness.³⁻⁵

Currently, the most commonly used clinical method to measure central corneal thickness is ultrasound (US) pachymetry. Recent studies have shown this method to have a high degree of intraoperator, interoperator, and inter-instrument reproducibility.⁶⁻⁹ However, this technique

requires corneal-probe contact, and so measurement may yield slightly thinner readings as a result of tissue indentation. Alternatively, placement of the probe exactly on the center of the cornea is operator dependent and crude, and consequently off-center placement may yield thicker measurements than the true central corneal thickness. Mild patient discomfort and risk for infection are additional concerns with a contact technique.

In recent years, several optical technologies have been introduced that offer the advantages of a noncontact technique and objective determination of the center of the

cornea. These include partial coherence interferometry (PCI),^{7,10-11} low-coherence reflectometry,¹² optical coherence tomography (OCT),¹³⁻¹⁵ and scanning-slit topography/pachymetry.^{9,13,16-18} McLaren and Bourne¹⁹ designed a pachymeter based on a photographic slitlamp connected to a video camera; a single slit video image is analyzed by dedicated software that determines the epithelial and endothelial borders of the cornea and hence its thickness. Although excellent repeatability and reproducibility have been reported for these instruments, the actual value of central corneal thickness measured may differ significantly between instruments, precluding their interchangeable use in clinical practice and research.

The Pentacam imaging device (Oculus), which recently became commercially available, uses a rotating Scheimpflug camera to image the anterior segment of the eye. It is a noncontact instrument that provides, in a single scan, anterior segment imaging (2-dimensional and 3-dimensional [3-D]), anterior and posterior corneal topography, complete corneal pachymetry, and densitometry of lens opacities. The optical low-coherence reflectometer (OLCR) pachymeter (Haag-Streit) is a new commercially available instrument that can be mounted on a slitlamp for measuring central corneal thickness. The manufacturer claims an accuracy and reproducibility of 1 μm for this instrument. Both devices use light instead of sound to measure corneal thickness and are noncontact systems. These features may lead to their widespread use.

The purpose of this study was to report initial experience with these 2 new devices. Specifically, we evaluated the intraoperator repeatability and interoperator reproducibility of central corneal thickness measurements with the Pentacam Scheimpflug system and the OLCR pachymeter and compared the actual value of central corneal thickness measurements with those obtained with a US pachymeter.

PATIENTS AND METHODS

The Pentacam system images the anterior segment of the eye by a rotating Scheimpflug camera. The patient is seated with his or

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her chin on a chinrest and forehead against the forehead strap and asked to fixate straight ahead on a fixation target. The operator visualizes a real-time image of the patient's eye on a computer screen, with the machine marking the pupil edge and center and the corneal apex, and can manually focus and align the image. Arrows are displayed on the screen that guide the operator's alignment of the instrument in the horizontal, vertical, and anteroposterior axes. To reduce operator-dependent variables, Pentacam's automatic release mode was used. In this mode, the instrument automatically determines when correct focus and alignment with the corneal apex have been achieved and then performs a scan. In less than 2 seconds, the rotating camera captures up to 50 slit images of the anterior segment, while minute eye movements are captured by a second camera and corrected simultaneously. Each slit image consists of 500 true elevation points. Mathematical software is used to detect edges in each slit image, including the epithelium and endothelium of the cornea, and a 3-D mathematical model of the anterior segment is constructed. The anterior surface of the cornea is calculated with no optical distortion and, according to the manufacturer, the tear film has no effect on measurements. Each successive layer, such as the posterior corneal surface and anterior lens surface, is calculated by ray tracing, with the calculation taking into account optical distortion. Single-point pachymetric measurements of the entire cornea are calculated from the calculated front and back surfaces. Since the center of the cornea is measured repeatedly during the rotational imaging process (in each of the images), very precise determination of central corneal thickness can be achieved. In this study, Pentacam Software V 1.04 was used.

The operating principles of OLCR pachymetry have been described.^{12,20} For measurements with the pachymeter, the instrument was mounted in place of the Goldmann tonometer. The patient was seated normally at the slitlamp unit and was instructed to look straight into a red axial laser diode beam. The instrument emits a second, lower diagonal diode laser beam, resulting in 2, 0.1 mm spots reflected from the cornea. The operator looked through the slitlamp microscope and moved the joystick until the 2 spots converged to 1 spot in the center of the pupil, determining correct working distance for the instrument. Further movement of the joystick brought the spot to the center of the cornea. The measuring infrared light emitting diode (LED) beam (1310 nm) is coaxial to the axial red laser diode beam. Due to the refractive index differences occurring at the air-to-cornea and cornea-to-anterior chamber interfaces, the measurement beam is reflected from the anterior and posterior corneal surfaces. These reflections reach back into the detector only when the LED beam strikes the corneal front and back surfaces perpendicularly. Only in the case of perpendicular incidence on both corneal surfaces are interference signals generated from them; in this case only, a single-point corneal thickness can be calculated based on the time delay between the 2 signals. The user identifies perpendicular incidence on the front corneal surface by the machine producing a sound. Further slight movement of the joystick leads to perpendicular incidence of the aiming beams on both the front and back surfaces of the cornea. In this situation, the machine produces a sound of higher pitch and records central corneal thickness. Repeated readings are automatically made and the mean and standard deviation (SD) displayed on a screen. In this study, the instrument was set to obtain 10 readings for each averaged measurement. This takes from 1 to a few seconds.

Consecutive patients were recruited from the outpatient clinic of the Assaf Harofe Medical Center. The study was conducted according to the tenets of the Declaration of Helsinki,

and patients gave informed consent after the nature and intent of the study had been fully explained to them. The exclusion criteria were ocular abnormalities other than cataract, history of eye disease, prior refractive surgery, and contact lens wear. All measurements were performed in the undilated right eye.

In the first experiment, the repeatability of the Pentacam camera, OLCR pachymeter, and US pachymeter was determined based on the definitions adopted by the British Standards Institution, as recommended by Bland and Altman.²¹ For each of the instruments, 10 successive scans were obtained by the same operator in the right eye of each of 4 patients (different patients for each instrument). With the Pentacam, the time between successive scans was approximately 15 seconds, the time needed for the instrument to calculate the data from each scan. To ensure that this experiment reflected 10 different measurements with no interdependence of successive measurements, between scans with the Pentacam or OLCR pachymeter, the joystick of the camera or slitlamp was fully retracted and then realigned. For each patient, the coefficient of repeatability was defined as the standard deviation of the difference from the mean of these repeat measurements divided by the mean response.

In the second experiment, interoperator reproducibility was determined. Two operators each obtained a single scan with the Pentacam of the right eye of each of 24 patients (15 women, 9 men; mean age 50.7 years \pm 17.4 [SD]). Each patient was asked to sit back and relax for 3 minutes between scans. The coefficient of interoperator reproducibility was defined as the SD of the differences between the pairs of measurements obtained by the 2 operators, divided by the average of the means of each pair of readings.

To compare central corneal thickness measurements obtained with the Pentacam system with those of the currently standard US pachymetry, following the second scan, the cornea was anesthetized with topical benoxinate hydrochloride 0.4% and 3 consecutive measurements were made by an ultrasonic pachymeter (pocket pachymeter, Quantel Medical). Prior to the study, the pachymeter was calibrated according to the manufacturer's instruction manual and tested with an appropriate test block. All ultrasonic measurements in this study were performed by the same investigator, who aimed to apply the probe as perpendicularly as possible on the central cornea. The mean of the 3 measurements was calculated and compared with the first operator's Pentacam measurement.

In a separate session, 3 consecutive measurements of central corneal thickness were made in the right eye of each of 16 patients (14 women, 2 men; mean age 48.4 \pm 18.9 years) by 1 operator using the OLCR pachymeter and following a 3-minute rest by a second operator. Each triplicate was averaged, and these means were used to determine interoperator reproducibility for the pachymeter. The coefficient of interoperator reproducibility was calculated as for the Pentacam system. Subsequently, central corneal thickness was recorded 3 times for the same eye of each participant by the first operator using the Pentacam, and the values were averaged. Computed tomography values were compared between the 2 instruments using the Wilcoxon paired measurement test and Bland-Altman plots, and the correlation coefficient was calculated.

RESULTS

The results of the repeatability study are shown in Table 1. The mean coefficient of repeatability for the 10 scans in the 4 patients was 0.84% for the Pentacam

Table 1. Coefficients of repeatability for the 4 patients in the repeatability study using the Pentacam, Pachymeter, and US pachymeter.

Patient	Coefficient of Repeatability (%)		
	Pentacam	OLCR Pachymeter	US Pachymeter
1	1.49	0.33	0.92
2	0.44	0.20	0.54
3	0.47	0.64	0.70
4	0.95	0.14	0.68
Mean	0.84	0.33	0.71

OLCR = optical low-coherence reflectometer; US = ultrasound

Scheimpflug system and 0.33% for the OLCR pachymeter, both values demonstrating excellent repeatability. The US pachymeter demonstrated similarly good repeatability with a coefficient of 0.71%.

The coefficient of interoperator reproducibility of the Pentacam Scheimpflug system was 1.10%; the intraclass correlation coefficient for interoperator reproducibility was 0.985. Figure 1 demonstrates a Bland-Altman plot of the pair difference against the mean values. The 95% limits of agreement, defined as mean interoperator difference ($\pm 1.96 \times$ SD of differences), were -10.2 to $+11.9 \mu\text{m}$. The Wilcoxon paired measurement test showed no statistically significant differences between the 2 sets of data ($P = .42$).

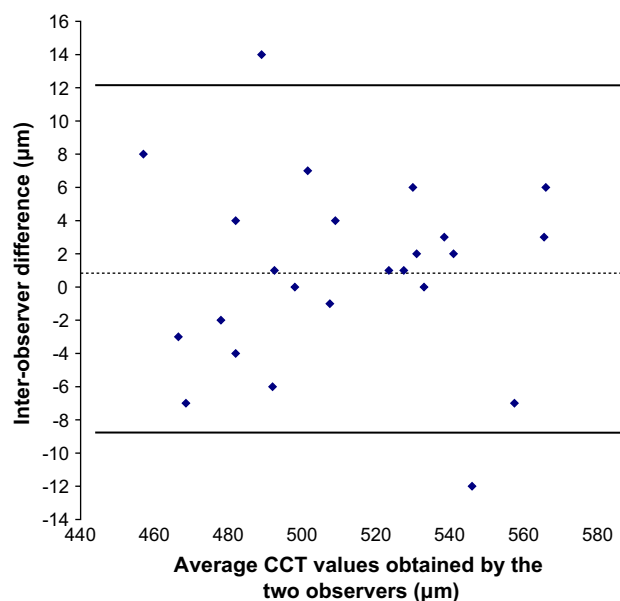


Figure 1. Differences in corneal thickness measurements between the 2 observers using Pentacam Scheimpflug system. The mean difference is represented by the dotted line and the 95% confidence limits, by the solid lines.

The coefficient of interoperator reproducibility for the OLCR pachymeter was 0.59%; the intraclass correlation coefficient for interoperator reproducibility was 0.995 (95% confidence interval, 0.987 to 0.998). Figure 2 demonstrates a Bland-Altman plot of the pair difference against the mean values. The 95% limits of agreement were -5.4 to $+7.0$. The Wilcoxon matched pairs test showed no statistically significant differences between the 2 sets of data ($P = .2$).

Comparison of central corneal thickness measurement with the Pentacam by 2 operators and with US pachymetry is summarized in Table 2. There was a high correlation between the Pentacam Scheimpflug system and US measurements, with an intraclass correlation coefficient of 0.883. Figure 3 demonstrates the differences between the 2 methods in a Bland-Altman plot of the pair difference against the mean values. The 95% limits of agreement were -23.4 to $+35.4$ μm . Mean difference between the 2 methods was 6.09 μm . The Wilcoxon paired measurement test showed that the difference between US and Pentacam central corneal thickness values approached statistical significance ($P = .05$).

The mean central corneal thickness values obtained using the OLCR pachymeter and Pentacam system are summarized in Table 3. Mean difference between the 2 methods was 1.7 μm . Intraclass correlation coefficient was 0.96. Figure 4 demonstrates the differences between the 2 methods in a Bland-Altman plot of the pair difference against the mean values. The 95% limits of agreement were -18.5 to $+17.2$. The Wilcoxon test showed no significant difference between the 2 measurements ($P = .88$).

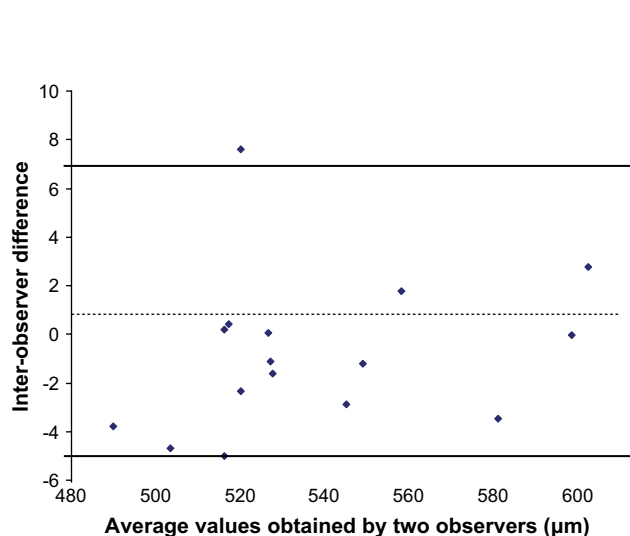


Figure 2. Differences in central corneal thickness measurements between 2 observers using the OLCR pachymeter. The mean difference is represented by the dotted line and the 95% confidence limits, by the solid lines.

Table 2. Mean central corneal thickness values in the right eye of 24 healthy patients with the Pentacam Scheimpflug device and a US pachymeter.

Method of Measurement	Mean Central Corneal Thickness (μm) \pm SD
Pentacam Scheimpflug – observer 1	511.38 ± 32.28
Pentacam Scheimpflug – observer 2	512.21 ± 32.07
US pachymeter	517.47 ± 28.69

US = ultrasound

DISCUSSION

Ophthalmic biometry should provide rapid, convenient, objective, and accurate measurements of ocular dimensions. For a new instrument to gain widespread use, it must provide measurements that have high intraoperator and interoperator reproducibility and are in agreement with or have a clear correlation to currently established methods. New instruments have been introduced in recent years that provide measurement of central corneal thickness in a convenient, noncontact way. These new instruments have been shown to have high repeatability and reproducibility. For example, OCT was shown to have a coefficient of repeatability of around 2% and a coefficient of interoperator reproducibility of 0.18%, with an intraclass correlation coefficient of 0.998.¹⁴ In a study comparing PCI and 3 US pachymeters, intraclass correlation coefficient for intraobserver variability was 0.999 for PCI compared with 0.987-0.995 for US.⁷ Marsich and Bullimore⁹

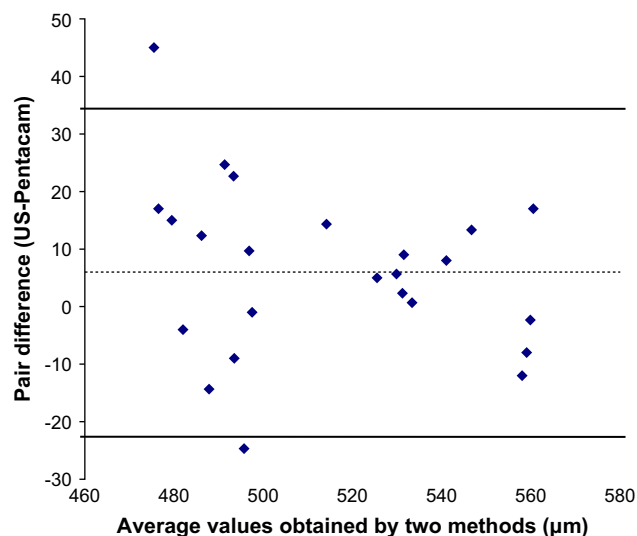


Figure 3. Differences in corneal thickness measurements between US pachymetry and the Pentacam Scheimpflug system. The mean difference is represented by the dotted line and the 95% confidence limits, by the solid lines.

Table 3. Mean central corneal thickness values in 16 healthy patients with the OLCR pachymeter and Pentacam Scheimpflug device.

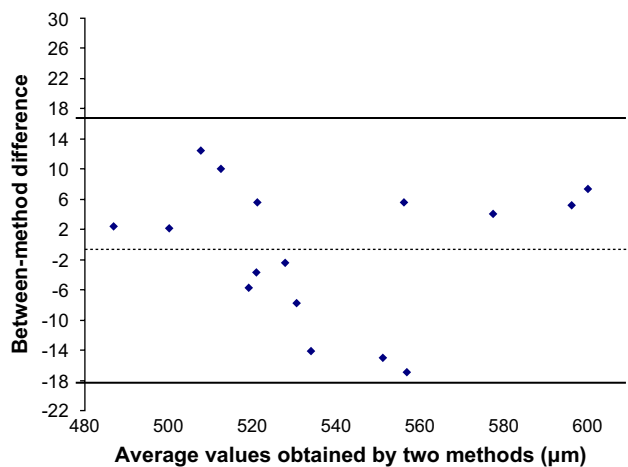
Device	Mean Central Corneal Thickness (μm \pm SD)
OLCR pachymeter – observer 1	537.0 \pm 33.0
OLCR pachymeter – observer 2	537.9 \pm 32.0
Pentacam Scheimpflug camera	538.7 \pm 33.0

OLCR = optical low-coherence reflectometry

performed 2 central corneal thickness measurements at the same time on different days and reported that the Orbscan achieved 95% limits of agreement of -10 to $+17$ μm compared with -22 to 24 μm by US. Suzuki et al.¹⁸ found that 2 consecutive measurements differed by a mean of 4.61 μm (0.86%) with Orbscan and 4.88 μm (0.89%) with US, with the 2 not statistically significantly different. We report similarly low (excellent) coefficients of repeatability and reproducibility for both the Pentacam Scheimpflug device and OLCR pachymeter. These indicate that a reliable estimate of central corneal thickness can be obtained in a single reading and is practically operator independent. The OLCR pachymeter had a lower (better) coefficient of repeatability and also a lower coefficient of reproducibility with narrower (roughly half) 95% limits of agreement compared with the Pentacam.

However, studies have shown significant differences in central corneal thickness measurements between different instruments, precluding their simple interchangeable use for clinical or research purposes.

Módis and coauthors¹⁶ reported large interinstrument differences in central corneal thickness measurements

**Figure 4.** Difference in the mean central corneal thickness values between OLCR pachymeter and Pentacam Scheimpflug device. The mean difference is represented by the dotted line and the 95% confidence limits, by the solid lines.

in 34 healthy eyes. Mean central corneal thickness was 547 ± 49 μm by noncontact specular microscopy, 580 ± 43 μm by US, 602 ± 59 μm by Orbscan, and 640 ± 43 μm by contact specular microscopy. A similar difference between US and Orbscan scanning-slit pachymetry was reported by Chakrabarti et al.,¹⁷ with Orbscan measurements, on average, 28 μm higher than US measurements. Bland-Altman plots showed that the 2 measurements differed by between -5 μm and 60 μm in 95% of cases. These and similar studies led to the Orbscan manufacturer incorporating an acoustic equivalent correction factor of 0.92 to adjust Orbscan measurements so that they are equivalent to those of US.

Suzuki et al.¹⁸ compared central corneal thickness measurements with an ultrasonic pachymeter, noncontact specular microscopy, and acoustically corrected Orbscan. In this study, similar measurements were recorded by US (548.1 ± 33.0 μm) and Orbscan scanning-slit topography (546.9 ± 35.4 μm). Noncontact specular microscopy gave significantly lower readings (mean 523.3 ± 31.4 μm) but was significantly linearly correlated both with Orbscan ($r = 0.846$) and US ($r = 0.897$), so that a conversion equation could be proposed to compare central corneal thickness measurements obtained by these different instruments.

Wong and coauthors¹³ compared central corneal thickness measurements of Orbscan (also with an acoustic factor of 0.92), US, and OCT. Mean central corneal thickness was similar for Orbscan (555.96 ± 32.41 μm) and US (555.11 ± 35.30 μm) and thinner for OCT (523.21 ± 33.54 μm). Again, excellent correlation was found between US and OCT measurements ($r = 0.945$), and when a correction factor of 32 μm was added to the OCT values, they became significantly equal to US measurements ($P < .05$). Bechmann et al.¹⁵ reported similar results, in which central corneal thickness measurements by OCT and US were separated by a constant difference of 49.4 ± 5.9 μm over the range of central corneal thickness, with a standardized regression coefficient of 0.988 between the 2 methods. Rainer et al.⁷ compared 3 US pachymetry devices with a prototype noncontact PCI device. Whereas the maximum difference in mean central corneal thickness was 5.9 μm between the 3 US pachymeters, mean central corneal thickness with PCI was 20.0 to 26.0 μm thinner than the US measurements.

We found that central corneal thickness measurements obtained by the Pentacam Scheimpflug device were highly correlated with those of the US pachymeter and the OLCR pachymeter. This is expected when one compares 2 devices that measure the same parameter.³ The agreement between the measurements, as proposed by Bland and Altman, better illustrates the clinical relevance of the difference between the 2 devices. Pentacam and US measurements

differed by a mean of only 6 μm . The 95% limits of agreement suggest that in 95% of cases, the difference in measurements between these 2 devices will range between $-23 \mu\text{m}$ and $+35 \mu\text{m}$. Pentacam and OLCR pachymeter measurements differed by only 1.7 μm on average, with the 95% limits of agreement suggesting that in 95% of cases, measurements with the OLCR pachymeter and Pentacam will differ by less than $\pm 18 \mu\text{m}$. How far apart measurements can be before they are considered significantly different must be determined by the clinician or experimenter for each application. However, it seems that for most practical purposes, measurements with these 3 instruments can be used interchangeably.

Considering the different technological methods and operating techniques of the 3 instruments, we found surprisingly small differences in their measurements. It should be pointed out that unlike US pachymeters, optical modalities such as the Pentacam and OLCR pachymeter conceivably may include the tear film in the measurement of corneal thickness, as the anterior reflecting surface is the air-tear film interface. The magnitude of this effect requires further study.

Anterior segment imaging based on the Scheimpflug principle is not in widespread use. A previous model (EAS-1000, Nidek Co. Ltd.) acquires a single image of the anterior segment, unlike the rotating Pentacam camera that acquires up to 50 images in each scan. It has been evaluated mainly in the assessment of anterior chamber depth and angle and objective densitometry of anterior segment opacities.²²⁻²⁸

Results obtained with prototypes of the OLCR pachymeter have been published.^{12,20} Genth et al.²⁰ compared preoperative central corneal thickness measurements by US with a prototype OLCR device mounted coaxially on an excimer laser system. They found a high correlation coefficient ($r = 0.97$, $P < .001$). However, a statistically significantly larger corneal thickness was measured with US pachymetry compared with OLCR (means $527 \pm 40 \mu\text{m}$ and $502 \pm 40 \mu\text{m}$, respectively).

Measurement of central corneal thickness with both the OLCR pachymeter and Pentacam Scheimpflug system was easy and convenient, with each reading lasting only a few seconds and each machine automatically determining correct alignment with the patient's cornea. With the currently standard US pachymetry, it is up to the operator to align the probe exactly at the center of the cornea and perpendicular to the corneal surface. Variations in probe placement, together with variable pressure with which the probe is applied to the corneal surface, may limit the accuracy of US measurements. Both new instruments offer the advantages of a noncontact technique. The decision of which device to use should take into account factors such as price and additional features. The OLCR pachymeter, for

example, is a dedicated device for the measurement of central corneal thickness, whereas the Pentacam Scheimpflug is an imaging device with a broader scope and potential uses.

In conclusion, we have shown that the Pentacam Scheimpflug device and the OLCR pachymeter can conveniently measure central corneal thickness with excellent repeatability and interoperator reproducibility. In addition, central corneal thickness values obtained with the Pentacam were similar to those obtained with a US pachymeter and with the OLCR pachymeter. Thus, the Pentacam device and the OLCR pachymeter are promising diagnostic modalities for the objective assessment of central corneal thickness. Further research is needed to corroborate whether central corneal thickness measurements by these 2 technologies can be used interchangeably and are more clinically useful than those obtained with US pachymetry.

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