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Full title: A comprehensive comparison of central corneal thickness measurement after LASIK

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Abstract

PURPOSE: To assess the repeatability and reproducibility of central corneal thickness (CCT) measurements by high resolution rotating Scheimpflug imaging (Pentacam, Oculus) and Fourier-domain optical coherence tomography (FD-OCT, RTvue-100, Optovue) after Laser In Situ Keratomileusis (LASIK), and to compare the agreement with ultrasound pachymetry (USP).

METHODS: Forty seven eyes of 47 patients after LASIK were included in the study. The first examiner took two successive Pentacam and RTvue CCT measurements and repeated once again by the second examiner to assess intra- and interobserver repeatability and reproducibility. After performing non-contact examinations, the corneas were measured by USP to compare the level of agreement among the three devices.

RESULTS: All Pentacam\textsubscript{center}, Pentacam\textsubscript{apex}, Pentacam\textsubscript{thinnest}, and RTvue CCT measurements demonstrated high intraobserver repeatability, with respective precision (1.96 within-subject standard deviation) and intraclass correlation coefficients (ICC) of 7.52\textmu m, 7.43\textmu m, 7.55\textmu m and 3.81\textmu m and 0.985, 0.986, 0.986 and 0.997; interobserver repeatability results were similar. All coefficients of variation were low: <1% for all measures. Compared with Pentacam and USP measurements, the RTvue measurement significantly underestimated CCT by a mean of 10.52 to 15.28\textmu m ($P < 0.001$) and 9.17\textmu m ($P < 0.001$), respectively. The agreement of USP with Pentacam and RTvue by Bland-Altman analysis spanned over 30 \textmu m. The agreement of Pentacam with RTvue spanned approximate 20 \textmu m.
CONCLUSIONS: Both Pentacam imaging and RTvue FD-OCT provide reliable and interchangeable measurement of CCT in post-LASIK corneas. However, they cannot be considered to be clinically interchangeable with USP.

Keywords: Corneal thickness, Optical coherence tomography, Rotating Scheimpflug photography, LASIK
Accurate and reliable determination of central corneal thickness (CCT) is necessary to evaluate patient eligibility for laser in situ keratomileusis (LASIK), planning the procedure, and managing follow-up.\(^1\)\(^-\)\(^2\) This is especially important in patients considered for enhancement surgery since their CCTs are more likely to be too thin for safe treatment.\(^3\)\(^-\)\(^4\)

Although Ultrasound pachymetry (USP) is the gold standard approach to measure CCT, high inter-observer and inter-instrument variation in measurement has been described.\(^5\)\(^-\)\(^6\) The measurement error of USP may arise from a lack of meticulous centration of the measurement, oblique incidence of the probe to the cornea, lack of a fixation light for gaze control, variability of sound speed across tissues, or even the effect of the topical anesthetic agent.\(^7\)\(^-\)\(^10\) After LASIK, CCT measurement can be confounded by loss of transparency in the postoperative cornea with accompanying corneal refractive index alterations, mistaken detection of the stromal interface as the posterior corneal surface, and alterations in corneal shape rendering reconstruction algorithms inappropriate.\(^11\)\(^-\)\(^13\)

In recent years a number of sophisticated imaging systems have been introduced which measure CCT. These techniques appear to be safe, flexible, and reliable. The original rotating Scheimpflug photography system (Pentacam, Oculus, Wetzlar, Germany) has been shown to provide reliable CCT measurements, which are highly agreeable with USP for normal corneas.\(^14\)\(^-\)\(^20\) Repeatability of corneal parameters with the original Pentacam Scheimpflug imaging after LASIK has also been demonstrated, albeit to a limited extent.\(^21\) More extensive evaluation is needed. The latest high resolution (HR) Pentacam Scheimpflug imaging system has a reformed optical design using a high resolution 1.45 megapixel camera
and is improved to maximally capture 138,000 data points in less than 2 seconds. To our knowledge no study to date has examined the repeatability and reproducibility of CCT by HR Pentacam Scheimpflug imaging in post-LASIK eyes.

Optical coherence tomography (OCT) is a noninvasive imaging modality, which uses coherence gating to obtain a cross-sectional microstructure of tissue. Recently, Fourier-domain OCT (FD-OCT) has demonstrated greater speed, shorter acquisition time, higher resolution and a greater signal-to-noise ratio compared to the conventional time-domain OCT (TD-OCT). The commercially available FD-OCT (RTvue-100, Optovue Inc, Fremont, California, USA) has a scan rate of 26,000 A-scans per second and an axial resolution of 5 µm; FD-OCT yields highly repeatable and reproducible measurements of retinal nerve fiber layer thickness. RTvue FD-OCT is also capable of obtaining high definition cross-sectional images of the cornea by adjusting a corneal adaptor module (CAM); this provides both central and regional pachymetry.

The present investigation aimed to evaluate the repeatability and reproducibility of CCT measurements using HR Pentacam Scheimpflug imaging and RTvue FD-OCT in post-LASIK eyes. Furthermore, this study also compared the agreement of measurements from HR Pentacam Scheimpflug imaging and RTvue FD-OCT with measurements obtained from USP within the same population.
PATIENTS AND METHODS

Subjects:

Subjects were 47 myopic patients who underwent LASIK treatment in the Refractive Surgery Department of the Affiliated Eye Hospital of Wenzhou Medical College between November 2008 and February 2009. All LASIK procedures were performed using the 400 Hz Mel-80 excimer laser (Carl Zeiss Meditec, Oberkochen, Germany) by the same surgeon (Q.W.). Flaps were created with a mechanical microkeratome (Moria, Antony, France); the intended flap thickness was 130 μm. Exclusion criteria included ocular disease, systemic disease, intraoperative or postoperative complications (eg, free flap, reepithelialization), or retreatment. The research protocol adhered to the tenets of the Declaration of Helsinki and was approved by the local ethics committee. Written informed consent was obtained from all patients. All measurements were performed in the right eye.

Procedure:

Part One:

In the first part of the study, the reliability of CCT measurements obtained by HR Pentacam Scheimpflug imaging and RTvue FD-OCT were investigated. Our definitions of reproducibility and repeatability were based on those adopted by the British Standards Institution, as recommended by Bland and Altman.26-28
The latest Pentacam rotating Scheimpflug camera system was used in this study. The patient was instructed to open both eyes and to fixate on a 475 nm blue light source in the center of the camera during scanning. The automatic release mode was used to reduce operator-dependent variables. The rotating camera captured 25 slit images of the anterior segment in less than 2 seconds. Each slit image consisted of 1,380 true elevation points that were analyzed by Pentacam Software 6.02r23. Only scans with an “Examination Quality Specification” of “OK” were chosen for analysis. The central pupil value of corneal thickness was recorded as CCT (Pentacam\textsubscript{center}), and the corneal thickness at the corneal apex (Pentacam\textsubscript{apex}) and thinnest location (Pentacam\textsubscript{thinnest}) were also recorded. Previous research has demonstrated some unreliability of the Pentacam pupil centre due to changes in pupil size during measurement, therefore inclusion in the study of two alternative Pentacam-derived CCT measures is appropriate.\textsuperscript{34}

The RTvue-100 used a super-luminescence diode as a low coherence light source, emitting light with a 50 nm bandwidth centered at 830 nm, corresponding to 5 µm depth resolution in tissue. The anterior segment imaging could be generated using a CAM, which was a set of lenses added on the probe to focus the OCT beam onto the cornea. Scanning with the FD-OCT was performed by using the corneal pachymetry protocol, which acquires eight evenly spaced 6-mm radial lines oriented 22.5 degrees from one another, consisting of 1024 A-scans per line in 0.31 seconds. The subject was asked to look at an internal fixation target. The center of the scan pattern was aligned with the corneal apex reflection visualized on the OCT images. The OCT image was determined when the reflection from the anterior apex of
the cornea saturated the imaging system and produced a vertical flare. The average reading displayed in the center was used for the FD-OCT analysis automatically using the recently available software version 3.6.

The CCT of each patient was measured using Pentacam Scheimpflug imaging and RTvue FD-OCT by two independent and experienced examiners. For each method, the first examiner (HJH) performed testing with both devices, taking two measurements with each. Subjects were then immediately rescanned by the other examiner (WDZ) using the same protocol although taking only one measurement with each device. After each acquisition, the device was moved backwards and realigned for the next scan to eliminate interdependence of successive measurements. The time for the instrument to calculate the data between successive scans was approximately 20 seconds for the Pentacam Scheimpflug imaging and 10 seconds for the RTvue FD-OCT. The total time to acquire all measurements did not exceed 10 minutes. For each method, differences between the 2 measurements obtained by the first examiner were used to assess intra-observer repeatability; the differences between the first measurements obtained by the two examiners were used to assess inter-observer reproducibility.

Part Two:

In the second part of the study, the interchangeability of CTT measurements using Pentacam Scheimpflug imaging, RTvue FD-OCT and USP in post-LASIK eyes were compared.
Following the non-contact examinations (Part One), the cornea was anesthetized with 0.5% topical proparacaine (Alcaine; Alcon Laboratories, TX, USA) in preparation for USP. The A-scan USP (SP-3000, Tomey Inc., Nagoya, Japan) was precalibrated for all measurements. The ultrasonic velocity was set at 1640 m/s. The patient was asked to fixate on a target on the ceiling. The pachymeter probe was brought in light contact with the cornea centrally and perpendicularly. Five readings were obtained, and the highest and the lowest values were excluded. The mean of the remaining 3 readings was calculated. In this case averaging of measures was performed as this is a standard approach.\textsuperscript{18, 29} This value was then compared with the three mean CCT values for Pentacam Scheimpflug imaging and the mean CCT value for RTvue FD-OCT, which were calculated from the two measurements taken by the first examiner. All measurements were taken between 10 AM and 5 PM to minimize the effect of changes in the physiological condition of the cornea.\textsuperscript{30-31}

**Statistical Analysis**

All statistical tests were performed using Statistical Package for Social Sciences for Windows version 13.0 (SPSS Inc, Chicago, Illinois, USA). Results are presented as mean ± standard deviation (SD). All data sets were checked for normality using the Kolmogorov-Smirnov statistic. All $P$ values were $> 0.05$, indicating that the data were normally distributed, and therefore it was appropriate to use parametric statistical tests.

To assess intra-observer repeatability, the within-subject SD ($S_w$) of two consecutive
measurements by the first examiner was calculated. Precision (repeatability coefficient) was defined as ± 1.96 $S_w$. The difference between a subject’s measurement and the true value from a statistical standpoint would be expected to be less than 1.96 $S_w$ for 95% of the observations. The 95% limits of agreement (LoA) were computed by mean difference ± 1.96 SD of the differences which provides an interval within which 95% of the differences between measurements are expected to lie. The within-subject coefficient of variation ($CV_w$, $100 \times S_w$/overall mean) was also calculated. Further statistical analysis for the intrasession reliability of the measurement method by both instruments was performed with intraclass correlation coefficients (ICC). The ICC was determined on the basis of analysis of variance for two-way mixed-effects model with an absolute agreement for consistency of individual measurements. ICC values can theoretically range from 0 to 1, with a higher value indicating less random or systematic differences in the measurements. To assess inter-observer reproducibility, inter-observer $S_w$, precision, $CV_w$, 95% LoA, and ICC were also calculated.

CCT measurements with the 3 methods were compared using a repeated-measures analysis of variance (ANOVA), with a Bonferroni correction for multiple comparisons, and Bland and Altman plots. Significance was set at $P \leq 0.05$.

RESULTS

The mean age of the patients was 23.5 ± 4.3 years (range, 18 to 34 years), and 23 patients (49%) were female. The mean post-LASIK period was 207.1 ± 151.2 days (range, 30 to 720 days).
The mean pre-LASIK refraction was $-5.70 \pm 1.83$ diopters (range, $-2.00$ to $-9.38$ diopters).

**Repeatability of CCT Measurements**

Table 1 presents the intraobserver repeatability statistics $S_w$, precision, $CV_w$, and ICC. Both Pentacam Scheimpflug imaging and RTvue FD-OCT demonstrated a high repeatability of CCT. The Bland-Altman plots (Figure 1) illustrate the variability between first and second measurements was smaller with RTvue FD-OCT than with Pentacam Scheimpflug imaging. There was no relationship between variability and mean CCT with either device (all $P$ values were $> 0.05$).

**Reproducibility of CCT Measurements**

Table 2 shows the interobserver reproducibility statistics $S_w$, precision, $CV_w$, and ICC. No statistically significant differences in CCT were noted between examiners ($P > 0.05$). Although both instruments performed well, the RTvue FD-OCT showed better reproducibility (Figure 2). There was no relationship between variability and mean CCT with either device (all $P$ values were $> 0.05$).

**Agreement of CCT measurements**
Table 3 shows that CCT measurements taken using RTvue FD-OCT (447.66 ± 33.57 μm) were significantly lower than Pentacam<sub>center</sub> (462.94 ± 31.51 μm, \( P < 0.001 \)), Pentacam<sub>apex</sub> (459.13 ± 31.87 μm, \( P < 0.001 \)), Pentacam<sub>thinnest</sub> (458.18 ± 32.29 μm, \( P < 0.001 \)) and USP (456.83 ± 32.66 μm, \( P < 0.001 \)). No statistically significant difference was found between Pentacam<sub>apex</sub> and USP measurements (\( P = 0.217 \)), and between Pentacam<sub>thinnest</sub> and USP measurements (\( P = 0.864 \)). The Bland–Altman plots showed that the 95% LoA between Pentacam Scheimpflug imaging and RTvue FD-OCT were lower than the values for other 2 pairs of devices (Figure 3) and that there were no relationships between agreement and mean CCT (all \( P \) values were > 0.05).

**DISCUSSION**

The use of validated and reliable measurement instruments is of critical importance for the clinical practice and interpretation of study results.\(^{34}\) It is crucial, therefore, to evaluate the precision and compare the accuracy of such instruments, particularly before they become widely applied in clinical practice and research settings. The present study demonstrated that HR Pentacam Scheimpflug imaging and RTvue FD-OCT have high repeatability and reproducibility in post-LASIK patients, although the FD-OCT performed slightly better compared with HR Pentacam Scheimpflug imaging. This is probably because the RTvue algorithm includes averaging of multiple points, measures pachymetry with greater speed and shorter acquisition time to reduced eye motion-related artifact, and has higher resolution which aids in distinguishing the anterior and posterior corneal surfaces; these
strategies all likely reduce variability. Importantly, we have demonstrated that a reliable CCT measurement can be obtained independent of operators and without numerous acquisitions as illustrated by the comparability of the intra- and inter-observer results. To our knowledge, this is the first study to assess the repeatability and reproducibility of CCT measurement following LASIK using HR Pentacam Scheimpflug imaging and RTvue FD-OCT, and to compare agreement with USP.

These reliability results are consistent with previous studies that have demonstrated that the original Oculus Pentacam provides reliable CCT measurement in normal corneas, keratoconus and corneal grafts (Table 4). However, many of the studies that used Pentacam Scheimpflug imaging in post-LASIK corneas were limited because they addressed the accuracy but not the precision of the original Oculus Pentacam in comparison to other pachymeters including optical and USP. To our knowledge only Jain et al have investigated the repeatability of CCT in post-LASIK eyes with original Oculus Pentacam, reporting a high degree of repeatability for the central, apical and thinnest pachymetry. However, that study did not correctly present Bland-Altman plots and their results are a little unclear. They assessed repeatability based on five successive scans obtained by the same operator in each patient, and plotted the difference of each reading from an average in each patient on the ordinate against the observation sequence on the abscissa. With such a statistical analysis, the readings are related so cannot be independent from each other.

Previous studies have demonstrated that the TD-OCT yielded highly reliable measurements of normal corneal thickness. Muscat et al. assessed the inter-operator variability of CCT by
Stratus OCT (Carl Zeiss Meditec, Dublin, CA) and found an excellent reproducibility (95% LoA of -3 to 4 μm, and an ICC of 0.998). Li et al reported high repeatability in anterior segments Visante TD-OCT (Carl Zeiss Meditec, Dublin, CA; the ICC and Sw values ranged between 0.96 and 0.98 and 4.9 μm and 7.3 μm, respectively). Kim et al found a small but significant systematic difference between two observers with slit-lamp OCT (Heidelberg Engineering, Dossenheim, Germany; mean, 6.9 μm; SD 10.9 μm). Li et al. reported the reproducibility of CCT by the Visante OCT was 1.7 μm (pooled SD) in post-LASIK corneas. A recent study by Keech et al showed RTvue provides a highly repeatable measure of corneal thickness at various locations in virginial eyes, with ICC ranging between 0.969 and 0.996. The outcomes in this study were similar to or better than TD-OCT studies. The repeatability (2.77 × Sw) was less than 5.5 μm (i.e., the difference between any two measurements for the same subject is expected to be less than 5.5 μm for 95% of all pairs of measurements). A change in CCT greater than 5.5 μm would therefore be more likely to represent actual change rather than measurement error. Therefore RTvue FD-OCT enables reliable detection of change of corneal thickness.

In the present study, HR Pentacam Scheimpflug imaging slightly overestimated CCT compared with USP by an average of 6.11 μm at central pupil but no statistically significant difference was found between Pentacam_{apex} and USP, and between Pentacam_{thinnest} and USP measurements. These differences are clinically insignificant and are consistent with previous studies that compared the original Pentacam system and USP for post-LASIK or PRK corneas (Table 5). However, the range of 95% LoA were 34.6 μm, 33.6 μm and -15.5 to 33.7 μm.
between Pentacam\textsubscript{center} vs. USP, Pentacam\textsubscript{apex} vs. USP and Pentacam\textsubscript{thinnest} vs. USP, respectively. While the means are comparable, the LoA are large which is due to the variability of both measures, particularly USP which has been shown to be larger than with Scheimpflug imaging\textsuperscript{16,20}. Whether this agreement is clinically satisfactory depends upon the clinical situation. This may, for example, alter the decision of whether a patient is suitable for LASIK enhancement or not. Therefore these methods should probably be considered not clinically interchangeable.

RTvue FD-OCT had a significantly lower mean CCT measurement compared to USP and Pentacam Scheimpflug imaging CCT measurements by a mean of 9.17\textmu m, 15.28 \textmu m, 11.47 \textmu m and 10.52 \textmu m at central pupil, apical and thinnest locations respectively, which agrees with findings in previous studies using OCT. Several studies demonstrated that CCT measured by OCT was generally thinner than that measured by USP and Pentacam. Ponce et al., Li et al., and Zhao et al. found the Visante OCT CCT measurement to be thinner than ultrasound by 7.5 \textmu m, 14.6 \textmu m, 16.5 \textmu m, respectively\textsuperscript{42,46-47} Ho et al report that Visante OCT measurements underestimate Pentacam corneal thickness in post-LASIK patients by a mean of 4.1 \textmu m\textsuperscript{37} More recently, Chen et al.\textsuperscript{48} showed that RTvue FD-OCT significantly underestimated CCT measurement compared with the HR Pentacam and USP in healthy, normal corneas, by a mean of 10.9 \textmu m and 5.63 \textmu m, respectively. Both RTvue FD-OCT and Visante TD-OCT use similarity methodology to identify the anterior and posterior corneal surfaces and transform distance between them into corneal thickness by computer analysis. The anterior corneal boundary delineated by the Visante OCT was positioned slightly below
the anterior corneal surface, leading to underestimation of corneal thickness. The faster scan speed and higher resolution of FD-OCT can reduce data acquisition time and improve edge detection. This difference may additionally be computational specific algorithm and reflected wave assessment. These factors may largely lead to underestimating the pachymetry with RTVue. The 95% LoA for the agreement between Pentacam Scheimpflug imaging and RTvue FD-OCT are narrow (approximate 20 μm) and were comparable to those found in the reproducibility studies mentioned above. Ciolino et al. compared original Pentacam Scheimpflug imaging and USP CCT in eyes that had undergone laser LASIK and demonstrates that 95% of the eyes differed in CCT measurements by -18.9 to 21.8 μm. Our 95% LoA between HR Pentacam Scheimpflug imaging and RTvue FD-OCT are even narrower and comparable to the reported range of -11 μm to 11 μm for the diurnal pachymetric variation of CCT, comparable to the repeatability of Pentacam, and comparable to reproducibility of flap thickness with and Moria LSK-1 and M2 Microkeratomes (the variation range of 19 to 24 μm). Therefore we propose that these systems can be used interchangeably in post-LASIK eyes for most clinical applications. While the mean difference can be adjusted for, the 95% LoA between RTvue and USP spans 32.5 μm. Again this suggests the two measures cannot be used interchangeably. This is especially important for LASIK enhancement surgery assessment where patients may have borderline corneal thickness. Underestimation of corneal pachymetry may lead to exclusion of some of these patients and, in general, to an overly conservative treatment plan. Conversely, overestimation can lead to inadvertent thinning of the stromal bed beyond 250 μm and, theoretically, may increase the risk for keratectasia.
The current study had several limitations. This type of study is hampered by the different algorithms each device uses for reporting CCT, yet one can only examine the results that each device reports. The RTvue reports a CCT which is an average of a number of central points which enhances its repeatability. The HR Pentacam reports several CCT measures, which are derived from the centre of the pupil, the corneal apex or the thinnest corneal point. Fortunately, the choice of CCT makes little difference to the interchangeability with other measures. Ultrasound pachymetry is theoretically performed over the pupil centre, suggesting this should be the standard, but it is unlikely that even the most experienced pachymetrist could discern whether they placed the probe at the corneal apex or the pupil centre. Indeed the poor repeatability of corneal USP undermines its position as the CCT measurement of choice. Perhaps it is time the ophthalmic industry moved to consider imaging systems as the CCT measure of choice. Another shortcoming is that the consecutive patients had a wide post-LASIK period range from 30 to 720 days. Since both Pentacam and RTvue FD-OCT rely on measurements of reflected light beams through the corneal tissues, the accuracy of pachymetry after refractive surgery may be affected when there are loss of corneal transparency and change of refractive index. Previous reports have demonstrated Orbscan II CCT measurements tended to be thinner in postoperative corneas and corneas with haze, while those of Pentacam were statistically stable in postoperative corneas and corneas with haze\textsuperscript{39, 52}. The outcomes cannot be influenced by corneal haze because the present study only included post-LASIK patients free of surgery complications, corneal haze and enhancements. Nevertheless, further research is necessary to detect if there are
differences in corneal thickness measurements at the one-week, one-month, three-months and one-year postoperatively between these device comparisons.

In summary, the HR Pentacam Scheimpflug imaging and RTvue FD-OCT demonstrated high repeatability and reproducibility for CCT measurements in post-LASIK eyes. However, it is important to emphasize that in clinical practice, measurement values are not directly interchangeable between both non-contact devices and USP as the LoA are relatively wide.
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REFERENCES


16. de Sanctis U, Missolungi A, Mutani B, Grignolo FM. Graft central thickness...


23. Liu B, Brezinski ME. Theoretical and practical considerations on detection performance of time domain, Fourier domain, and swept source optical coherence tomography. J Biomed


31. Read SA, Collins MJ. Diurnal variation of corneal shape and thickness. Optom Vis Sci
40. Ciolino JB, Khachikian SS, Belin MW. Comparison of corneal thickness measurements by ultrasound and scheimpflug photography in eyes that have undergone laser in situ


44. Li Y, Shekhar R, Huang D. Corneal pachymetry mapping with high-speed optical coherence tomography. Ophthalmology 2006;113:792-799 e792.


Figure Legends

**Figure 1.** Bland-Altman Plots of the mean difference between the first and second measurements against the mean CCT readings taken with the Pentacam High Resolution Rotating Scheimpflug Photography (A, B, C) and RTvue Fourier-domain Optical Coherence Tomography OCT(D). The 95% limits of agreement are shown with dashed lines, and the solid line represents the mean difference between these measurements.

**Figure 2.** Bland-Altman Plots of the mean difference between examiners’ measurements against the mean CCT readings taken with the Pentacam High Resolution Rotating Scheimpflug Photography (A, B, C) and RTvue Fourier-domain Optical Coherence Tomography OCT (D). The 95% limits of agreement are shown with dashed lines, and the solid line represents the mean difference between these measurements.

**Figure 3.** Bland-Altman plots comparing CCT between Pentacam<sub>center</sub> and USP (A), Pentacam<sub>center</sub> and RTvue (B), Pentacam<sub>apex</sub> and USP (C), Pentacam<sub>apex</sub> and RTvue (D), Pentacam<sub>thinnest</sub> and USP (E), Pentacam<sub>thinnest</sub> and RTvue (F), and RTvue and USP (G). The 95% limits of agreement are shown with dashed lines, and the solid line represents the mean difference between these measurements.
<table>
<thead>
<tr>
<th>Device</th>
<th>Mean Difference (μm) ± SD</th>
<th>$S_w$ (μm)</th>
<th>Precision (μm)</th>
<th>$CV_w$ (%)</th>
<th>ICC (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentacam$_{center}$</td>
<td>-0.77 ± 5.43</td>
<td>3.83</td>
<td>7.52</td>
<td>0.83</td>
<td>0.985 (0.974 to 0.992 )</td>
</tr>
<tr>
<td>Pentacam$_{apex}$</td>
<td>-0.81 ± 5.36</td>
<td>3.79</td>
<td>7.43</td>
<td>0.83</td>
<td>0.986 (0.975 to 0.992 )</td>
</tr>
<tr>
<td>Pentacam$_{thinnest}$</td>
<td>-0.83 ± 5.44</td>
<td>3.85</td>
<td>7.55</td>
<td>0.84</td>
<td>0.986 (0.975 to 0.992 )</td>
</tr>
<tr>
<td>RTvue</td>
<td>0.94 ± 2.62</td>
<td>1.95</td>
<td>3.81</td>
<td>0.43</td>
<td>0.997 (0.994 to 0.998 )</td>
</tr>
</tbody>
</table>

Pentacam$_{center}$ = central corneal thickness measured by the Pentacam, Pentacam$_{apex}$ = apical corneal thickness measured by the Pentacam, Pentacam$_{thinnest}$ = thinnest corneal thickness measured by the Pentacam, SD = standard deviation, $S_w$ = within-subject standard deviation, Precision = 1.96 x $S_w$, $CV_w$ = within-subject coefficient of variation, ICC = intraclass correlation coefficient, CI = confidence interval, LoA = limits of agreement according to Bland-Altman method.
<table>
<thead>
<tr>
<th>Device</th>
<th>Mean Difference (μm) ± SD</th>
<th>$S_w$ (μm)</th>
<th>Precision (μm)</th>
<th>$CV_w$ (%)</th>
<th>ICC (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentacam$_{center}$</td>
<td>0.47 ± 5.85</td>
<td>4.11</td>
<td>8.05</td>
<td>0.89</td>
<td>0.984 (0.971 to 0.991)</td>
</tr>
<tr>
<td>Pentacam$_{apex}$</td>
<td>-0.62 ± 5.44</td>
<td>3.83</td>
<td>7.50</td>
<td>0.83</td>
<td>0.986 (0.992 to 0.992)</td>
</tr>
<tr>
<td>Pentacam$_{thinnest}$</td>
<td>-0.38 ± 4.83</td>
<td>3.39</td>
<td>6.65</td>
<td>0.74</td>
<td>0.989 (0.981 to 0.994)</td>
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<tr>
<td>RTvue</td>
<td>1.04 ± 2.40</td>
<td>1.84</td>
<td>3.60</td>
<td>0.41</td>
<td>0.997 (0.994 to 0.998)</td>
</tr>
</tbody>
</table>

Pentacam$_{center}$ = central corneal thickness measured by the Pentacam, Pentacam$_{apex}$ = apical corneal thickness measured by the Pentacam, Pentacam$_{thinnest}$ = thinnest corneal thickness measured by the Pentacam, SD = standard deviation, $S_w$ = within-subject standard deviation, Precision = $1.96 \times S_w$, $CV_w$ = within-subject coefficient of variation, ICC = intraclass correlation coefficient, CI = confidence interval, LoA = limits of agreement according to Bland-Altman method.
Table 3. Paired t test, Correlation Values and Limits of Agreement (LoA) among 3 different Devices.

<table>
<thead>
<tr>
<th>Device Pairings</th>
<th>Mean Difference (μm) ± SD</th>
<th>95% LoA (μm)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentacam_center – USP</td>
<td>6.11 ± 8.84</td>
<td>-11.2 to 23.4</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Pentacam_center – RTvue</td>
<td>15.28 ± 5.43</td>
<td>4.6 to 25.9</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Pentacam_apex – USP</td>
<td>2.30 ± 8.56</td>
<td>-14.5 to 19.1</td>
<td>0.217</td>
</tr>
<tr>
<td>Pentacam_apex – RTvue</td>
<td>11.47 ± 5.12</td>
<td>1.4 to 21.5</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Pentacam_thinnest – USP</td>
<td>1.35 ± 8.62</td>
<td>-15.5 to 18.2</td>
<td>0.864</td>
</tr>
<tr>
<td>Pentacam_thinnest – RTvue</td>
<td>10.52 ± 5.28</td>
<td>0.2 to 20.9</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>RTvue – USP</td>
<td>-9.17 ± 8.28</td>
<td>-25.4 to 7.1</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

Pentacam_center = central corneal thickness measured by the Pentacam, Pentacam_apex = apical corneal thickness measured by the Pentacam, Pentacam_thinnest = thinnest corneal thickness measured by the Pentacam, USP = Ultrasound pachymetry, SD = Standard deviation.

* 2 tailed.
Table 4. Summary of Previous Studies for the Repeatability and Reproducibility of Central CornealThickness Measurements by Pentacam Rotating Scheimpflug Photography.

<table>
<thead>
<tr>
<th>First Author</th>
<th>Study Population</th>
<th>Eyes (Patients) (n)</th>
<th></th>
<th>Repeatability</th>
<th>Reproducibility</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>ICC (95% CI)</td>
<td>95% LoA (μm)</td>
<td>ICC (95% CI)</td>
</tr>
<tr>
<td>de Sanctis</td>
<td>Normal</td>
<td>20 (20)</td>
<td>0.99 (0.98 to 0.99)</td>
<td>-12.5 to 12.5</td>
<td>0.98 (0.97 to 0.99)</td>
</tr>
<tr>
<td>Lackner *</td>
<td>Normal</td>
<td>24 (24)</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>O'Donnell**</td>
<td>Normal</td>
<td>21 (21)</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>Miranda **</td>
<td>Normal</td>
<td>23 (23)</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>Miranda **</td>
<td>Normal</td>
<td>23 (23)</td>
<td>†</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>Miranda **</td>
<td>Keratoconus</td>
<td>33 (33)</td>
<td>0.98 (0.95 to 0.99)</td>
<td>-14.5 to 14.2</td>
<td>0.98 (0.96 to 0.99)</td>
</tr>
<tr>
<td>Ucakhan</td>
<td>Keratoconus</td>
<td>19 (19)</td>
<td>0.988 (0.981 to 0.992)</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>Ucakhan</td>
<td>Keratoconus</td>
<td>28 (28)</td>
<td>0.998 (0.978 to 0.994)</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>Ucakhan</td>
<td>Keratoconus</td>
<td>15 (15)</td>
<td>0.982 (0.945 to 0.996)</td>
<td>†</td>
<td>†</td>
</tr>
<tr>
<td>de Sanctis</td>
<td>Keratoconus</td>
<td>20 (20)</td>
<td>0.96 (0.92 to 0.99)</td>
<td>-12.8 to 22.2</td>
<td>0.95 (0.91 to 0.99)</td>
</tr>
</tbody>
</table>

ICC = intraclass correlation coefficient, CI = confidence interval, LoA = limits of agreement according to Bland-Altman method.

* Represents that the measurements between two examiners, ** Represents that the measurements between two session.
† Represents that the information was not provided within the article.
ⁿ Represents the repeatability measurements 48 hours later, ⁰ Represents the repeatability measurements within a few seconds, ² Represents the repeatability measurements 1 hour later, ³ Represents the repeatability measurements 1 week later, ⁴ Represents pupil centre, ⁵ Represents corneal apex.
Table 5. Findings of Studies Comparing Ultrasound Pachymetry (UP) and Pentacam Rotating Scheimpflug Photography in Eyes That Have Undergone Laser In Situ Keratomileusis (LASIK) or Photorefractive Keratectomy (PRK).

<table>
<thead>
<tr>
<th>First Author</th>
<th>Study Population</th>
<th>Eyes (Patients) (n)</th>
<th>Mean CCT (μm) ± SD</th>
<th>Mean Difference (μm) ±SD</th>
<th>95% LOA</th>
<th>Pearson Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ciolino</td>
<td>Post LASIK</td>
<td>104 (53)</td>
<td>506 ± 22</td>
<td>505 ± 32</td>
<td>-1.4 ± 10</td>
<td>-20 to 20</td>
</tr>
<tr>
<td>Ho</td>
<td>Post LASIK</td>
<td>103 (52)</td>
<td>430.66 ± 40.23</td>
<td>438.2 ± 41.18</td>
<td>-7.54 ± 15.06</td>
<td>-37.06 to 21.98</td>
</tr>
<tr>
<td>Hashemi*</td>
<td>Post LASIK</td>
<td>60 (30)</td>
<td>468 ± 48</td>
<td>478 ± 51</td>
<td>-9 ± 15</td>
<td>-39 to 19</td>
</tr>
<tr>
<td>Kim(1 to 3 months)</td>
<td>Post PRK</td>
<td>24 (15)</td>
<td>476 ± 46.4</td>
<td>468 ± 39.9</td>
<td>+7.54 ± 12.2</td>
<td>-16.4 to 31.4</td>
</tr>
<tr>
<td>Kim(&gt; 4 months)</td>
<td>Post PRK</td>
<td>21 (14)</td>
<td>494 ± 33.1</td>
<td>481 ± 33.1</td>
<td>+12.6 ± 10.1</td>
<td>-7.2 to 32.4</td>
</tr>
</tbody>
</table>

CCT = central corneal thickness, SD = standard deviation; LoA = limits of agreement according to Bland-Altman method.

* Represents that the surgical procedure for myopic correction was LASIK in 38 eyes, PRK in 14 eyes, and PRK plus mitomycin-C in 8 eyes.

† Represents that the information was not provided within the article.