A Comparison between Scheimpflug Imaging and Optical Coherence Tomography in Measuring Corneal Thickness

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Purpose: To assess the repeatability and reproducibility of 3 rotating Scheimpflug cameras, the Pentacam (Oculus, Wetzlar, Germany), Sirius (Costruzione Strumenti Oftalmici, Florence, Italy), and Galilei (Ziemer, Biel, Switzerland), and 1 Fourier-domain optical coherence tomography (FD-OCT) system, the RTvue-100 OCT (Optovue Inc., Fremont, CA), in measuring corneal thickness.

Design: Evaluation of diagnostic test.

Participants: Sixty-six right eyes of 66 healthy volunteers, whose mean age $\pm$ standard deviation (SD) was 35.39$\pm$10.06 years (range, 18–55 years).

Methods: Corneal thickness measurements obtained by each system included central corneal thickness (CCT), thinnest corneal thickness (TCT), and midperipheral corneal thickness (MPCT), measured at superior, inferior, nasal, and temporal locations at a distance of 1 and 2.5 mm from the corneal apex. In the first session, 3 consecutive measurements were performed by the same operator to assess intraobserver repeatability and by a second operator to assess interobserver reproducibility. Measurements were repeated in the second session scheduled 1 day to 1 week later. The mean values obtained in the 2 sessions by the first operator were used to investigate the intersession reproducibility.

Main Outcome Measures: Intraobserver repeatability and interobserver and intersession repeatability of corneal thickness measurements, as calculated by means of within-subject SD, test–retest repeatability, coefficient of variation (COV), and intraclass correlation coefficients.

Results: The precision of CCT, TCT, $CT_{2\ mm}$ (midperipheral corneal thickness [MPCT] with a distance of 1 mm from the corneal apex), and $CT_{5\ mm}$ (midperipheral corneal thickness [MPCT] with a distance of 2.5 mm from the corneal apex) measurements was high with all 4 systems. The COV was $\leq$1.16%, 0.94%, and 1.10% for repeatability, interobserver reproducibility, and intersession reproducibility, respectively. The 4 devices offered better interobserver reproducibility than intersession reproducibility for all measurements. The $CT_{superior\text{-}5\ mm}$ (midperipheral corneal thickness [MPCT], measured at superior locations with a distance of 2.5 mm from the corneal apex) measurements showed the poorest repeatability and reproducibility. The Galilei revealed the best precision of CCT, TCT, and $CT_{2\ mm}$ measurements.

Conclusions: Both Scheimpflug imaging and FD-OCT offer highly repeatable and reproducible measurements of CCT and MPCT. The precision was lower in the midperipheral superior quadrant.

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Reliable and precise measurements of corneal thickness are crucial to many clinical and research applications in ophthalmology.[1] Central corneal thickness (CCT) plays a major role in the diagnosis of glaucoma, pre-refractive surgery screening, and all diseases resulting in corneal edema.[2–7] Midperipheral corneal thickness (MPCT) also is important for conditions such as keratoconus and corneal cross-linking, radial keratotomy, and intrastromal ring placement.[8–10]

For some time, ultrasonic pachymetry (USP) has been the most commonly used method to measure corneal thickness and is still regarded as the gold-standard technique. However, USP has some drawbacks because it requires contact with the cornea, and its reliability can be influenced by variable factors, including topical anesthesia and operator skill to manually place the USP probe as perpendicularly as possible to the center of the cornea.[11–13] Subsequently, many noncontact instruments have been developed to overcome the disadvantages of USP. Among these, Fourier-domain (FD) optical coherence tomography (OCT) and Scheimpflug imaging systems play a major role.

Several studies have investigated the repeatability and reproducibility of these instruments, but some important information about corneal thickness measurements is still lacking. For example, the repeatability and reproducibility

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of CCT and thinnest corneal thickness (TCT) measurements with the Pentacam rotating Scheimpflug camera (Oculus, Wetzlar, Germany) and the RTVue (Optovue Inc., Fremont, CA), an FD-OCT system, have been extensively studied.[13–20] On the contrary, the precision of peripheral corneal measurement with these devices rarely has been assessed.[21,22] The repeatability of more recent Scheimpflug cameras, such as the Sirius (Costruzione Strumenti Oftalmici, Florence, Italy) and Galilei (Ziemer, Biel, Switzerland), also has been investigated. It has been demonstrated that the Sirius system provides high intraobserver repeatability of CCT and MPCT measurements.[23] However, no study has reported the interobserver or intersession reproducibility of corneal thickness with this device. For Galilei, high intraobserver repeatability and interobserver reproducibility of CCT and TCT measurements have been described.[24,25] However, the intersession reproducibility of CCT and TCT measurements and the precision of MPCT have not been investigated.

The aim of this study is to comprehensively assess, for the first time, the intraobserver repeatability, interobserver reproducibility, and intersession reproducibility of CCT, TCT, and MPCT measurements with all the above-mentioned instruments: the Pentacam, Sirius, Galilei, and RTvue-100 OCT.

Subjects and Methods

Subjects

This prospective study, involving 66 right eyes of 66 healthy subjects, was conducted in the Eye Hospital of Wenzhou Medical College. The research protocol was in accordance with the Declaration of Helsinki and approved by the Office of Research Ethics, Wenzhou Medical College. Written informed consent was obtained from each subject.

The exclusion criteria included recent contact lens wear (rigid contact lens within 4 weeks and soft contact lens within 2 weeks), corrected vision less than 20/20, intraocular pressure more than 21 mmHg, corneal astigmatism more than 2.0 diopters (D), active ocular pathology, and any history of ophthalmic surgery. Before inclusion in this study, all eyes underwent a complete ophthalmic examination, including refraction, slit-lamp microscopy, noncontact tonometry, Topolyzer corneal topography (WaveLight Technologie AG, Erlangen, Germany), and ophthalmoscopy.

Instruments

The Pentacam Standard uses a rotating Scheimpflug camera (180 degrees) to provide a 3-dimensional scan of the anterior segment of the eye. A monochromatic slit-light source (diode-emitting blue light at 475 nm) rotates around the optical axes of the eye. Within 2 seconds, 25 slit images of the anterior segment are captured. Each slit image possesses 500 true elevation points, and 25 000 points are obtained. For each slit image, mathematic software is used to detect edges, including the epithelium and endothelium of the cornea. Finally, a 3-dimensional mathematic image of the anterior segment is generated.

A rotating Scheimpflug camera and a small-angle Placido disk topographer with 22 rings are combined in the Sirius. A full scanning acquires a series of 25 Scheimpflug images (meridians) and 1 Placido top-view image. The Placido image provides ring edges, and height, slope, and curvature data are obtained by the arc-step method with conic curves. Scheimpflug images showed the profiles of anterior cornea, posterior cornea, anterior lens, and iris. The data for the anterior surface are finally determined by merging the Placido image and the Scheimpflug images using a proprietary method. However, other data of internal structures (posterior cornea, anterior lens, and iris) are obtained solely from the Scheimpflug images.

The Galilei, using a monochromatic slit-light source (diode-emitting blue light at 470 nm), combines dual Scheimpflug cameras and a Placido disk to measure both anterior and posterior corneal surfaces. It requires 1 or 2 seconds to make a whole scan, which obtains more than 122 000 points. During the rotating scan, the Placido and Scheimpflug data of the corneal information are simultaneously obtained. The anterior corneal measurements are made by a proprietary method of merging the 2 types of data. Two Scheimpflug slit images are made by the dual camera from opposite sides of the illuminated slit, and the data are averaged. Meanwhile, the dual camera simultaneously tracks decentration due to eye movements.

The RTvue-100 is an FD-OCT featuring 5 μm of depth resolution in tissue and high-magnification imaging of the cornea within 0.04 seconds. It adopts a super-luminescence diode as a low coherence light source, which emits light with a 50-nm bandwidth centered at 830 nm. A corneal-anterior module long lens adapter with low magnification is added to the RTvue to image the anterior segment. The corneal pachymetry protocol acquires 8 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 apex-centered mode was selected to perform the scanning in this study.

Measurement Technique

All eyes were measured without dilation between 10 AM and 5 PM to minimize the effects of diurnal variation in corneal shape and thickness.[26] Corneal thickness measurements of all eyes were performed using the Pentacam, Galilei, Sirius, and RTvue-100 OCT. All measurements with each instrument were performed by 2 well-trained operators in a dim room according to the manufacturers' guidelines. The examiners were masked to the results of the previous measurements obtained from each device. For each subject, the orders of the 4 devices and the 2 operators were both arranged randomly. The testing sequence of the measurements with these devices was randomly chosen to avoid methodological bias. MedCalc Statistical Software version 10.0.1.0 (MedCalc Software, Inc., Mariakerke, Belgium), predetermined generate random sample program. All subjects were positioned in the headrest and asked to fixate on the target on the center of the camera without blinking during each scan. Only scans with an "examination quality specification" of "OK" were retained for analysis, whereas the substandard ones were deleted and repeated. Each subject was instructed to blink once completely just before scanning to spread an optically smooth tear film over the cornea. After each measurement, the subject was asked to sit back and the system was realigned for the next measurement.

For each device, 3 consecutive measurements were performed by each operator (P.C. and H.Y.J.). Those 3 standard measurements of each device obtained by each operator were used to study intraoperator repeatability. For the interoperator reproducibility of each system, the values of 3 successive measurements were averaged to obtain the mean value. The differences between the mean values obtained by the 2 operators were used to assess the interoperator reproducibility. Measurements were repeated in the second session scheduled 1 day to 1 week later, at almost the same time as the first session, by the same first examiner using the same protocol. The mean values obtained at different time points by the first operator were compared for the intersession reproducibility of each system. Meanwhile, the interobserver reproducibility and intersession reproducibility of these 4 systems were compared.

Corneal thickness measurements obtained by each system included CCT, TCT, and MPCT (Fig 1, available at http://aaojournal.org). The CCT was measured by each instrument at the corneal apex. The TCT was obtained at the thinnest point of the cornea. The MPCT was measured at the superior, inferior, nasal, and temporal locations at a distance of 1 or 2.5 mm from the corneal apex. Therefore, 8 categories of MPCT were chosen for analysis, including 4 directions and 2 distances. They were defined as corneal thickness (CT): $CT_{2\ mm}$ ($CT_{superior\text{-}2\ mm}$, $CT_{inferior\text{-}2\ mm}$, $CT_{nasal\text{-}2\ mm}$, and $CT_{temporal\text{-}2\ mm}$) and $CT_{5\ mm}$ ($CT_{superior\text{-}5\ mm}$, $CT_{inferior\text{-}5\ mm}$, $CT_{nasal\text{-}5\ mm}$, and $CT_{temporal\text{-}5\ mm}$).

Statistical Analysis

Statistical analysis was performed using SPSS software for Windows version 17 (SPSS Inc., Chicago, IL) and Microsoft Office Excel (Microsoft Corp, Redmond, WA). A P value less than 0.05 was considered to be statistically significant. The distributions of the datasets were checked for normality using Kolmogorov−Smirnov tests. The results indicated that the data were normally distributed ($P > 0.05$).

To determine the intraobserver repeatability of each device, within-subject standard deviation (Sw), test−retest repeatability (TRT), within-subject coefficient of variation (COV), and intraclass correlation coefficients (ICCs) were calculated for the 3 repeated measurements obtained by the first and second observers. The TRT was defined as 2.77 Sw, which means an interval within which 95% of the differences between measurements are expected to lie. The COV was calculated as the ratio of the Sw to the overall mean. A lower COV is associated with higher repeatability. The closer the ICC is to 1, the better the measurement consistency. To assess interobserver reproducibility, the mean of the 3 readings from each observer was first calculated for each device, and then interobserver Sw, 2.77 Sw, COV, and ICCs also were calculated. To assess intersession reproducibility, the mean of the 3 readings from 2 sessions by the first same observer was calculated for each device, and then intersession Sw, 2.77 Sw, COV, and ICCs also were calculated.

Results

This study enrolled 66 right eyes of 66 subjects (33 men, 33 women). The mean age of the subjects was 35.39±10.06 years (range, 18−55 years). The mean spherical equivalent refraction was −3.82±2.42 D (range, 0.75 to −11.75 D).

Intraobserver Repeatability

The intraobserver repeatability of corneal thickness measurements obtained by each operator was high with all systems (Tables 1−4). The COV was lower than 1.0% for all measurements except $CT_{5\ mm}$, which showed the poorest repeatability with each device and both operators (Figs 2 and 3, available at http://aaojournal.org). In regard to the intraobserver repeatability of $CT_{5\ mm}$, $CT_{superior\text{-}5\ mm}$ was the worst among the 4 locations with each instrument. The intraobserver repeatability of $CT_{5\ mm}$ was slightly better with the Sirius.

The Galilei provided the best intraobserver repeatability of CCT, TCT, and $CT_{2\ mm}$, and the Pentacam presented the worst results for these measurements.

Interobserver Reproducibility

The interobserver reproducibility of corneal thickness measurements was high with the 4 systems (Tables 5−8, available at http://aaojournal.org). The COV was lower than 1.0% for all measurements. For each device, the interobserver reproducibility of CCT, TCT, and $CT_{2\ mm}$ was better than that of $CT_{5\ mm}$ (Fig 4, available at http://aaojournal.org). In regard to the interobserver reproducibility of $CT_{5\ mm}$, the $CT_{superior\text{-}5\ mm}$ was the worst in the 4 locations with each instrument but the RTvue, which showed a poorer result in the nasal sector. Among the 4 devices, the Galilei provided the best values for CCT, TCT, and $CT_{2\ mm}$ measurements, and the Pentacam presented the worst values. However, the interobserver reproducibility of $CT_{5\ mm}$ was slightly worse with the RTvue (Fig 4, available at http://aaojournal.org).

Intersession Reproducibility

The intersession reproducibility of corneal thickness measurements was high with the 4 systems (Tables 9−12, available at http://aaojournal.org). The COV was ≤1.1% for all measurements. Each device provided better intersession reproducibility of CCT, TCT, and $CT_{2\ mm}$ than that of $CT_{5\ mm}$ (Fig 5, available at http://aaojournal.org). In regard to the intersession reproducibility of $CT_{5\ mm}$, $CT_{superior\text{-}5\ mm}$ was the worst in the 4 locations with each instrument but the Pentacam, which had the poorest reproducibility in the temporal sector. Among the 4 devices, the Galilei provided the best intersession reproducibility of CCT, TCT, and $CT_{2\ mm}$ measurements, whereas Pentacam presented the worst one. The intersession reproducibility of $CT_{5\ mm}$ was better for the Galilei and Sirius (Fig 5, available at http://aaojournal.org).

Comparison between Interobserver Reproducibility and Intersession Reproducibility of Corneal Thickness Measurements

For each device, the interobserver reproducibility of CCT, TCT, $CT_{2\ mm}$, and $CT_{5\ mm}$ was higher than the intersession reproducibility (Figs 6−9, available at http://aaojournal.org).

Discussion

Repeatable and reproducible measurements are mandatory for both the clinical practice and research settings.[27,28] To our knowledge, this is the first study to comprehensively evaluate the precision (i.e., intraobserver repeatability, interobserver reproducibility, and intersession reproducibility) of CCT, TCT, and MPCT measurements with the 4 systems included in our analysis: the Galilei, Pentacam, Sirius, and RTvue OCT. Overall, the results of our study indicated that the precision of corneal measurements was high for all parameters with all devices except the 5-mm superior region.

Previous studies investigated only some of these issues. Results similar to ours have been reported for CCT and TCT in normal corneas.[13,14,23−25] Nam et al[13] and Chen et al[14] found high intraobserver repeatability and interobserver reproducibility when measuring CCT with the RTvue and, to a lesser extent, with the Pentacam. Milla et al[23] and Savini et al[24] reported high repeatability of CCT measurements by the Sirius and Galilei, respectively. In regard to MPCT, Khoramnia et al[22] and Milla et al[23] reported good repeatability with the Pentacam and Sirius, respectively.

The results of the present study also suggest some interesting observations. First, the measurements of CCT,

Table 1. Intraobserver Repeatability of Pentacam (Oculus, Wetzlar, Germany) in Measuring Corneal Thickness (N=66)

Parameter	Observer	Mean (μm) ± SD	Sw (μm)	TRT (μm)	COV (%)	ICC
Center	1st	538.82±26.46	3.48	9.65	0.65	0.983
	2nd	538.75±25.93	3.73	10.32	0.69	0.980
Thinnest	1st	535.78±26.36	3.55	9.84	0.66	0.982
	2nd	535.33±26.20	3.76	10.43	0.70	0.980
Superior 2 mm	1st	555.35±27.26	4.02	11.12	0.72	0.979
	2nd	555.49±26.56	4.25	11.78	0.77	0.975
Inferior 2 mm	1st	542.51±26.76	3.84	10.63	0.71	0.980
	2nd	541.96±26.56	3.75	10.38	0.69	0.980
Nasal 2 mm	1st	549.43±26.77	4.68	12.96	0.85	0.970
	2nd	549.19±26.38	4.36	12.07	0.79	0.973
Temporal 2 mm	1st	540.05±26.74	4.08	11.29	0.75	0.977
	2nd	539.82±26.28	4.34	12.01	0.80	0.973
Superior 5 mm	1st	626.15±30.89	6.12	16.96	0.98	0.962
	2nd	626.31±29.95	6.86	19.01	1.10	0.949
Inferior 5 mm	1st	592.09±28.26	5.57	15.42	0.94	0.962
	2nd	591.15±28.32	5.38	14.90	0.91	0.965
Nasal 5 mm	1st	605.54±28.38	5.08	14.08	0.84	0.969
	2nd	604.48±28.09	5.21	14.44	0.86	0.966
Temporal 5 mm	1st	585.38±28.33	6.21	17.19	1.06	0.953
	2nd	584.91±28.59	5.91	16.38	1.01	0.958

COV = within-subject coefficient of variation; ICC = intraclass correlation coefficient; SD = standard deviation; Sw = within-subject standard deviation; TRT = test−retest repeatability (2.77 Sw).

TCT, and $CT_{2\ mm}$ (and to a lesser extent $CT_{5\ mm}$) are highly repeatable and reproducible with the 4 devices, and the precision is adequate for all clinical purposes. Although the differences among the 4 instruments are not clinically relevant (because they cannot influence any clinical decision), it should be highlighted that the Galilei provided the best results. The excellent repeatability of corneal thickness measurements by the Galilei has been reported previously[24,25,29−32] and seems to be related to the use of 2 rotating Scheimpflug cameras, 180 degrees apart, which simultaneously capture slit images from opposite sides of the slit record. This system has been designed to overcome the errors associated with scans obtained at an oblique angle and compensate for eye micromovements during the examination. Other results of the present study are in good agreement with those reported by previous studies. Savini et al[33] reported that the repeatability of the Sirius was slightly worse than that previously reported for the Galilei

Table 2. Intraobserver Repeatability of Sirius (Costruzione Strumenti Oftalmici, Italy) in Measuring Corneal Thickness (N=66)

Parameter	Observer	Mean (μm) ± SD	Sw (μm)	TRT (μm)	COV (%)	ICC
Center	1st	542.14±27.12	3.17	8.79	0.59	0.986
	2nd	540.61±27.22	2.78	7.69	0.51	0.990
Thinnest	1st	539.18±27.11	2.85	7.88	0.53	0.989
	2nd	537.73±27.20	2.83	7.84	0.53	0.989
Superior 2 mm	1st	559.34±27.76	3.40	9.42	0.61	0.985
	2nd	557.82±27.84	3.31	9.17	0.59	0.986
Inferior 2 mm	1st	544.00±27.15	3.06	8.49	0.56	0.987
	2nd	542.76±27.23	2.96	8.19	0.54	0.988
Nasal 2 mm	1st	552.84±27.40	3.08	8.54	0.56	0.987
	2nd	551.36±27.56	2.80	7.76	0.51	0.990
Temporal 2 mm	1st	545.43±27.50	2.92	8.10	0.54	0.989
	2nd	544.17±27.65	2.88	7.98	0.53	0.989
Superior 5 mm	1st	625.79±30.30	4.28	11.84	0.68	0.980
	2nd	623.87±29.76	6.57	18.21	1.05	0.953
Inferior 5 mm	1st	586.96±29.00	3.83	10.62	0.65	0.983
	2nd	585.82±28.77	4.00	11.07	0.68	0.981
Nasal 5 mm	1st	600.86±28.55	3.69	10.21	0.61	0.984
	2nd	599.22±28.79	3.61	9.99	0.60	0.984
Temporal 5 mm	1st	582.40±29.18	3.42	9.47	0.59	0.986
	2nd	580.65±29.61	3.65	10.10	0.63	0.985

COV = within-subject coefficient of variation; ICC = intraclass correlation coefficient; SD = standard deviation; Sw = within-subject standard deviation; TRT = test−retest repeatability (2.77 Sw).

Table 3. Intraobserver Repeatability of Galilei (Ziemer, Biel, Switzerland) in Measuring Corneal Thickness (N=66)

Parameter	Observer	Mean (μm) ± SD	Sw (μm)	TRT (μm)	COV (%)	ICC
Center	1st	548.10±26.41	1.82	5.05	0.33	0.995
	2nd	548.66±26.50	1.75	4.84	0.32	0.996
Thinnest	1st	545.62±26.36	1.47	4.07	0.27	0.997
	2nd	546.33±26.49	1.31	3.64	0.24	0.998
Superior 2 mm	1st	563.13±27.04	3.29	9.11	0.58	0.985
	2nd	563.80±27.22	3.52	9.75	0.62	0.983
Inferior 2 mm	1st	551.26±26.36	2.11	5.85	0.38	0.994
	2nd	551.82±26.36	2.20	6.09	0.40	0.993
Nasal 2 mm	1st	558.66±26.50	2.33	6.47	0.42	0.992
	2nd	559.26±26.38	2.58	7.15	0.46	0.990
Temporal 2 mm	1st	550.69±27.07	2.07	5.73	0.38	0.994
	2nd	551.15±27.20	1.66	4.60	0.30	0.996
Superior 5 mm	1st	619.07±29.98	6.93	19.21	1.12	0.948
	2nd	619.40±29.98	6.99	19.37	1.13	0.948
Inferior 5 mm	1st	588.01±27.13	5.55	15.38	0.94	0.959
	2nd	587.99±27.28	5.00	13.85	0.85	0.967
Nasal 5 mm	1st	602.90±27.54	4.78	13.25	0.79	0.970
	2nd	603.21±26.84	4.97	13.77	0.82	0.966
Temporal 5 mm	1st	579.95±28.91	4.25	11.78	0.73	0.979
	2nd	580.49±29.25	4.02	11.14	0.69	0.981

COV = within-subject coefficient of variation; ICC = intraclass correlation coefficient; SD = standard deviation; Sw = within-subject standard deviation; TRT = test−retest repeatability (2.77 Sw).

(COV, 0.43%−0.52% vs. 0.32%−0.43%).[24] They also pointed out that the repeatability of the Sirius system was slightly better than that of the Pentacam reported by Nam et al[13] (COV, 0.43%−0.52% vs. 0.67% and 0.68%). Several authors[13,14,28,33] showed that the repeatability of corneal thickness measurements by the Pentacam was worse than that for FD-OCT, which is consistent with the results of the present study. The possible reasons for the better repeatability with the RTVue OCT than the Pentacam may be related to the higher scanning speed of the RTvue, which may overcome the eye motion−related artifact, and the higher resolution of the RTVue, which may help in the detection of the anterior and posterior corneal surfaces.[13,28]

Second, for each device and with both operators, the precision of CCT, TCT, and $CT_{2\ mm}$ measurements was better than that of $CT_{5\ mm}$ measurements. Previous studies agree with our results: they report more variability of measurements for MPCT than for CCT.[22,34,35] There are several reasons that

Table 4. Intraobserver Repeatability of RTVue (Optovue Inc., Fremont, CA) in Measuring Corneal Thickness (N=66)

Parameter	Observer	Mean (μm) ± SD	Sw (μm)	TRT (μm)	COV (%)	ICC
Center	1st	532.81±26.24	2.17	6.01	0.41	0.993
	2nd	532.55±26.85	2.04	5.65	0.38	0.994
Thinnest	1st	528.06±26.49	1.65	4.57	0.31	0.996
	2nd	527.84±26.61	1.84	5.09	0.35	0.995
Superior 2 mm	1st	542.42±26.58	3.44	9.53	0.63	0.983
	2nd	542.50±26.79	3.07	8.51	0.57	0.987
Inferior 2 mm	1st	533.40±26.81	2.86	7.93	0.54	0.989
	2nd	533.79±27.01	2.77	7.66	0.52	0.990
Nasal 2 mm	1st	539.95±26.81	3.00	8.31	0.56	0.988
	2nd	540.12±26.62	2.89	8.01	0.54	0.988
Temporal 2 mm	1st	533.23±26.25	2.69	7.46	0.51	0.990
	2nd	532.74±26.52	2.83	7.83	0.53	0.989
Superior 5 mm	1st	591.72±29.22	6.86	19.01	1.16	0.947
	2nd	593.14±28.66	5.46	15.13	0.92	0.965
Inferior 5 mm	1st	562.39±28.46	4.36	12.09	0.78	0.977
	2nd	562.23±28.58	4.20	11.63	0.75	0.979
Nasal 5 mm	1st	575.45±28.07	5.05	13.99	0.88	0.968
	2nd	574.53±28.08	5.08	14.08	0.88	0.968
Temporal 5 mm	1st	554.32±27.60	4.24	11.74	0.76	0.977
	2nd	554.39±27.82	4.30	11.90	0.77	0.977

COV = within-subject coefficient of variation; ICC = intraclass correlation coefficient; SD = standard deviation; Sw = within-subject standard deviation; TRT = test−retest repeatability (2.77 Sw).

may explain this finding: (1) the overlap of Scheimpflug images in the center of the cornea is greater than that in the periphery because of the rotation of the camera around the optical axis, and the points captured for the same location by the Scheimpflug camera decrease sharply from the central cornea to the periphery[22]; (2) the use of an unstable reference point as the center of the pupil instead of the vertex cornea could lead to the error of repeatability of peripheral pachymetry with a system based on Scheimpflug photography[36]; (3) the periphery of vertical scans is more subject to artifacts derived from the eyelids, which can cover the upper and lower parts of the cornea.[11] In this regard, no instrument provided a clear advantage when measuring the $CT_{5\ mm}$, although the Sirius showed a slightly higher intraobserver repeatability and interobserver reproducibility. The intraobserver repeatability of $CT_{superior\text{-}5\ mm}$ measurements was the worst in the 4 $CT_{5\ mm}$ locations with each instrument. It is likely that a major contribution to this result is due to the wider corneal covering by the upper lid with respect to the lower lid.

Third, the precision of the 4 investigated devices was comparable to or better than that of other devices in current clinical use. Several studies have assessed the precision of the Orbscan (Bausch & Lomb, Rochester, NY), a scanning slit topography system. When assessing repeatability, the COV of CCT measurements by the Orbscan was found to be approximately 1%,[37] which is the same value of the 4 devices in the present study. Another repeatability study found an ICC of 0.972,[38] which is only slightly lower than the corresponding values of the present study. The intersession reproducibility (TRT of 32.1 μm) of the Orbscan II also was significantly poorer than those of the instruments investigated in this study.[38,39] The precision of CCT, as measured by a time-domain OCT (Visante, Carl Zeiss Meditec, Dublin, CA), was similar: The COVs were 0.3%, 0.5%, and 0.5% for intraobserver repeatability, interobserver reproducibility, and intersession reproducibility, respectively. In the same study, the precision of Visante has been reported to be high for paracentral measurements, with COVs close to those of the Galilei.[40]

Comparison with CCT measurements by other instruments (less commonly used) reveals higher precision with the 4 instruments used in this study. The interobserver TRT of time-domain OCT (Stratus; Carl Zeiss Meditec) and the intersession TRT of noncontact specular microscope (EM-3000; Tomey, Nagoya, Japan) and confocal microscopy (ConfoScan 3; Nidek, Freemont, CA) were reported to be 17.0, 21.6, and 60.0μm, respectively.[11,39,41]

Finally, with each device, the interobserver reproducibility of CCT, TCT, $CT_{2\ mm}$, and $CT_{5\ mm}$ was higher than the intersession reproducibility. This suggests that the diurnal variability of corneal thickness at different time points had more effect than changing from the first to the second observer.

Study Limitations

First, we did not investigate the level of agreement among the 4 instruments; this is the subject of an ongoing study. Second, further work is required to assess the precision of the 4 optical methods when applied to unusual corneas, such as corneal edema, keratoconus, or eyes after refractive surgery. Third, this study did not include USP, which is still regarded as the gold-standard technique. Previous studies have compared the repeatability and reproducibility of CCT measurements by USP and optical methods. Some authors found that the measurements by USP and optical techniques (Scheimpflug imaging and OCT) showed similarly high repeatability and reproducibility.[16,42] Nam et al[13] reported that the Pentacam offered poorer repeatability compared with USP in healthy eyes, whereas de Sanctis et al[43] observed better repeatability and reproducibility of Pentacam in eyes with keratoconus. Because these studies were limited by a smaller sample than ours or showed other flaws (e.g., the inclusion of both eyes of the same individual), even an indirect comparison with our data would be inappropriate. Therefore, further investigation is warranted to compare the reliability of the USP with that of the 4 devices in our study. Fourth, the location of TCT was not analyzed in this study for 2 instruments: Sirius and Galilei. Further study is required to investigate the precision of the location of TCT using the 4 devices.

In conclusion, the 4 imaging devices (i.e., the Pentacam, Sirius, Galilei, and RTvue) showed high precision when measuring CCT and MPCT, although these values showed a lower repeatability and reproducibility, especially in the superior quadrant.

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